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# Naval Ocean Research and Development

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## Coastal Secchi Depth Atlas

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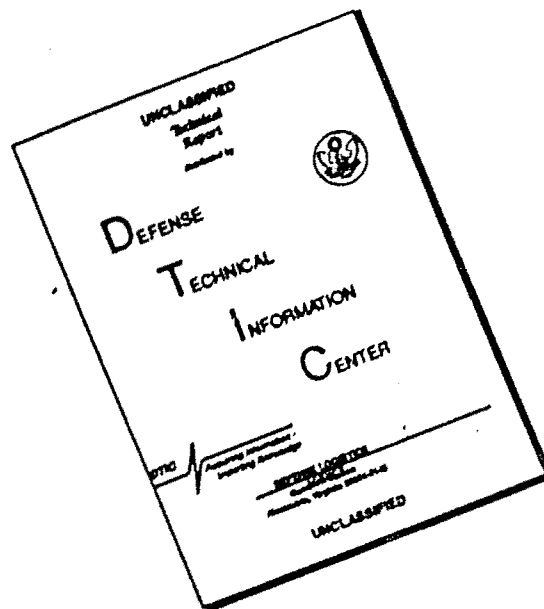
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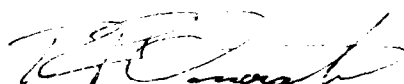
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## Foreword

Ocean optical properties significantly influenced performance of electro-optical systems presently being designed and constructed for the Defense Mapping Agency. The temporal and spatial distribution of these properties is highly variable, especially in coastal areas. Oceanographic atlases of these properties offer preliminary assessments of environmental constraints and focus future environmental research on more regional studies.



R. P. Onorati, Captain, USN  
Commanding Officer, NORDA

## Executive summary

A seasonal Secchi depth atlas has been developed for the world's coastlines. Optical data have been compiled from data gathered by the National Oceanographic Data Center and from open literature for water depths less than 500 meters. These data have been averaged by one-degree squares, sorted by season, and placed in a category of six classes of Secchi depth ranges. Four charts were used to cover the world at a scale of 1:12,233,000, and four seasons were selected to encompass 3-month intervals. Additionally, annual mean Secchi depths have been compiled in four charts. Secchi depth data were found for approximately 50% of the world's coastlines. In the areas where no optical data were available other oceanographic, meteorologic, and geomorphic data sources were used to estimate the expected Secchi depth ranges.

Global distribution of coastal Secchi depths indicates a high percentage of relatively clear waters. Less than 5% of the coastlines are shown to have less than 5-meter Secchi depth values. Little seasonal changes in a global scale in the percentage of each range were observed. The highest percentage of coastal waters has Secchi depth values between 15 and > 25 meters.

Secchi depth values show high temporal and spatial variability in certain coastal regions, even though the amount of data was highly limited. This variability suggests that improved techniques of compiling coastal optical properties, such as through use of satellites, be examined both to aid in understanding historical ship data and to serve as an additional optical data source.

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# Coastal Secchi depth atlas

## I. Introduction

Recent developments within the oceanographic community have improved data collection and handling procedures. These developments have shown that spatial and temporal variability of oceanographic parameters are much higher than previously surmised. Attempts to compile oceanographic data into an atlas format, such as for ocean temperature, salinity, and currents, have been somewhat successful. Ocean optical data has been quite restrictive, since major problems exist in which data techniques and lack of the basic optical relationships with physical or biochemical properties are not well understood. For these reasons the development of a seasonal optics atlas has not been feasible.

A comprehensive study of ocean optical properties was done by Frederick (1970) that was regional in extent and did not address the seasonal optical variability. Seventeen regions were studied, and statistical relationships were obtained between optical and other oceanographic properties. Another coastal turbidity study by Lepley (1968) was performed in which the water clarity of the world was classified based on photographs from the Gemini mission. The resolution in this study was extremely gross and did not describe the seasonality of coastal waters.

The coastal regions have an extremely high variability of oceanographic parameters, since these areas are responsive to local meteorological and coastal processes. Similarly, water optical properties have an extremely high variability in coastal areas because they respond to changes in biology, chemistry, and geological processes.

The necessity for a coastal optics data base arose from requirements of the Defense Mapping Agency (DMA), which is developing coastal hydrographic charting systems (Van Norden and Litts, 1979). These system capabilities are constrained by the water optical properties in which they operate. The seasonal distribution of the coastal optical properties provides a method by which planning operational surveys for coastal areas utilizing these charting systems can be effectively and efficiently achieved. Proper planning will increase the system performance and accuracy. The variability of the optical properties is also a strong indication of the biological, physical and geological processes occurring within a region, and provides an improved understanding of the oceanography when coupled with other parameters.

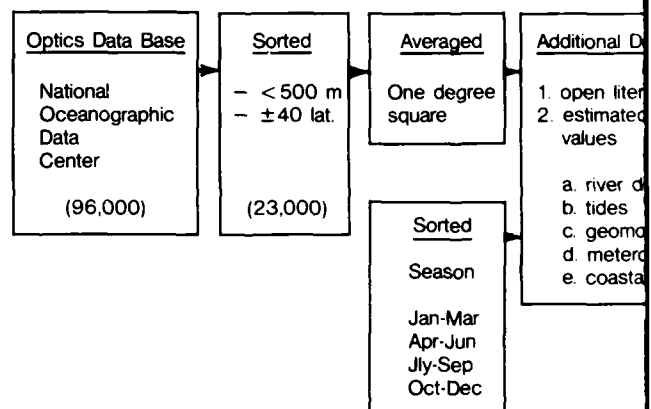


Figure 1. Flow chart for development

The establishment of an optics data base for global conditions required selection of an optical property in which numerous measurements have been made. Also, this property should be standardized such that various investigators' data can be jointly utilized. Although the Secchi depth measurement is not the most quantitative optical property, this measurement did meet the above-mentioned criteria and was selected as the basis for this global coastal atlas.

The objective of this report is to quantify the variability of coastal optical properties by using historical measurements of coastal optical properties, or by inferring the optical properties from response to coastal/oceanographic processes and meteorological conditions.

The coverage area of this coastal atlas is limited to all coastlines from 40°N to 40°S, except for the United States coastal waters. Extensive optics literature for U.S. coastal waters is available (Arnone, 1982, and Van Norden and Litts, 1979).

## II. Methods

Figure 1 represents the flow chart by which the coastal Secchi depth atlas was developed. The steps in this process will be discussed in some detail.

The basic data base from which the optical data was established was taken from the National Oceanographic Data Base (NODC).

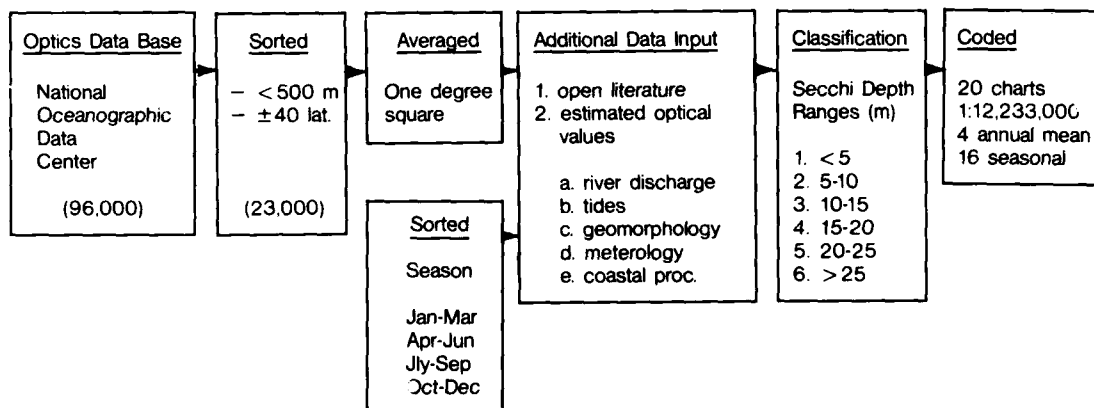


Figure 1. Flow chart for development of coastal Secchi depth atlas.

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These estimated 96,000 Secchi depths for worldwide waters were screened for coastal values by eliminating all Secchi depths in waters greater than 500 m. The remaining 23,000 worldwide data points were used in this coastal atlas study. Selection of this depth figure was somewhat subjective in that by selection of data less than 100 m, the amount of available data was reduced considerably, and atlas development would be greatly impeded. It is recognized that waters at 500 m depth may have considerable different optical properties than those waters in shallow waters. This problem is inherent in atlas development and should be taken into consideration in examination of the final atlas.

These 23,000 data points were then sorted into one-degree squares such that the horizontal coastal variability could be averaged. For each one-degree square bordering a coastline or having water depth less than 500 m, the average Secchi depth was obtained. This has the effect of smoothing the large horizontal variation that could occur if values were obtained from various offshore distances. Examination of the variability of the data for each one-degree square suggests the estimate of the averaging process. However, the statistical analysis of this variance of the data for each is misleading if only a few data points exist within a one-degree square. The high variance could indicate extremely high horizontal variability or an insufficient number of data points.

Next, the values for each one-degree square were sorted into four seasons. The seasonal annual mean for each square was com-

puted. The oceanographic world has substantially differed of several seasonal atlases selected for the entire atlas.

- January-March.
- April-June.
- July-September.
- October-December.

Regions that do not necessitate (e.g., monsoon season, Indian Ocean) consideration upon examination of other types of oceanographic data utilized in compiling the atlas.

The seasonal optical data was classified into one of six Secchi depth ranges by a mechanism to permit rapid selection and allowed for a color coded chart. The Secchi depth ranges are:

Range	Code
< 5	1
5-10	2
10-15	3
15-20	4
20-25	5
> 25	6

These ranges were selected to compare the coastal optical water properties with other optical properties. The schemes will be discussed.

A series of four base charts were developed. The hydrographic chart numbers 6010, 6011, 6012, and 6013 were used to code the data. The charts were at a scale of one-degree squares. They are:

Chart	Coverage
1	North & South Atlantic Ocean
2	Western India Ocean & African Coast

Data Input	Classification	Coded
Literature Sat optical  Discharge Es Morphology Terology Astal proc.	Secchi Depth Ranges (m)  1. < 5 2. 5-10 3. 10-15 4. 15-20 5. 20-25 6. > 25	20 charts 1:12,233,000 4 annual mean 16 seasonal

# ent of coastal Secchi depth atlas.

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Next, the values for each one-degree square were sorted into four seasons. The seasonal annual mean for each square was com-

puted. The oceanographic climate of various regions around the world has substantially different seasons. To avoid the development of several seasonal atlases for various regions, four seasons were selected for the entire atlas development:

- January-March.
- April-June.
- July-September.
- October-December.

Regions that do not necessarily reflect these oceanographic seasons (e.g., monsoon season, Indian Ocean) should be taken into consideration upon examination of the atlas. As will be described later, other types of oceanographic and meteorologic conditions were also utilized in compiling the season variability of coastal optical properties.

The seasonal optical data for each one-degree square were next classified into one of six Secchi depth ranges. This provided a mechanism to permit rapid screening of the data for regional trends and allowed for a color coded method of placing the data on the charts. The Secchi depth ranges follow:

Range Code	Range (m)	Chart Color
1	< 5	Brown
2	5-10	Yellow
3	10-15	Orange
4	15-20	Green
5	20-25	Blue
6	> 25	Purple

These ranges were selected to permit a rapid method of classifying the coastal optical waters. Examination of how these ranges compare with other optical properties and water classification schemes will be discussed later.

A series of four base charts obtained from DMA (compiled from hydrographic chart numbers 6004, 6005, 6006, 6007, 6008, 6009, 6010, 6011) were used to compile the worldwide optics data base. The charts were at a scale of 1:12,233,000 and were divided in one-degree squares. They are labeled in the following fashion:

Chart	Coverage Area	Longitude
1	North & South Americas Atlantic Ocean	5°E-95°W
2	Western Indian Ocean African Coasts	5°E-70°E

- |   |  |            |
|---|--|------------|
| 3 | Western Pacific, Indonesia,<br>Australia, Eastern Indian Ocean | 70°E-165°E |
| 4 | East and Central Pacific                                       | 165°E-95°W |

The coverage of each of these charts for the world is shown in Figure 2. Therefore, a total of 16 charts representing the four seasons on four charts of the world has been developed. In addition, the annual mean coastal Secchi depth values are represented on the four world charts, which resulted in a total of 20 charts represented in Plates 1-20.

The NODC data base, which provided the framework on which the atlas was developed, has insufficient Secchi depth data available for complete world coastal coverage. Large amounts of these data are concentrated in specific regions. For these reasons it was necessary to supplement the data base with optics data reported in open literature. These optics data were also limited, and in many cases, the data have to be converted to Secchi depth values. Several studies from the Naval Postgraduate School (Murdock, 1980) were also compiled within this atlas. For instances where contoured data was available at a resolution greater than the one-degree square, the data was used without loss of detail. The open literature on ocean optical properties is contained in several bibliographies (Arnone, 1982; Tucker, 1982; Hickman 1979), and the reader is directed to these regional studies if a more detailed requirement is necessary.

Results of the extensive open literature search still left a large gap with regard to the seasonal variation of coastal optics needed to complete the atlas. Based on additional sources of oceanographic, meteorological and coastal information, water optical properties were inferred. The data base was extended, first by examination of the Secchi depth values. For example, if a square was surrounded by a specific range of Secchi depths, then the same range was assigned to it. The color code was striped in this one-degree square rather than colored in solidly to signify that the data had been inferred.

An extension of this extrapolation procedure was utilized for several coastlines where no data was available. The assignment of the Secchi range was based on oceanographic/coastal processes, meteorologic conditions, geomorphic processes, and other local conditions; for example, proximity to major river mouths, major off-shore currents, upwelling zones, etc. Several of the parameters that influence optical properties will be discussed in a following section.

A Soviet atlas (Isokov, 1953) of summer and winter water transparency was also consulted as a data source, although it does not contain the detail in the coastal area. The Soviet atlas appears more relevant to deeper oceanic waters, since some coastline areas were found to conflict with some regional Secchi depth data found in the data base.

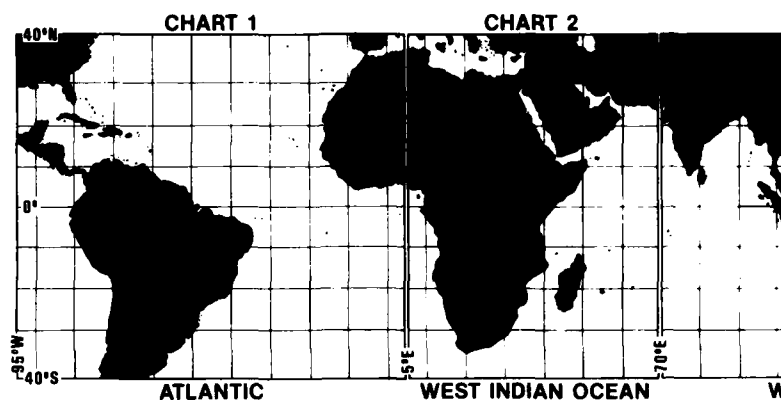


Figure 2. Geographical coverage of the atlas.

Examination of the 20 color plates indicates that the extent of optical data immediately available is rapidly discerned for the worldwide coastlines by the solid colors shown in the plates. The striped values, which constitute at least 50% of the coastlines, indicate that no optics data was found and that other sources of information were used to determine the Secchi depth range. The actual techniques and methods for relating the oceanographic climate to waters optical parameters will be described in the following sections.

### III. Difficulties and problems

Foremost in the problems encountered in generating the coastline atlas is the insufficient amount of data. The inference techniques implemented are limited, and actual in situ measurements are required to validate the procedures used.

In obtaining data in coastal regions, the spatial variability is difficult to characterize from ship-collected data. Averaging optical properties with a one-degree square leads to a bias toward the deeper water optical values. Measurements in shallow water are quite restrictive due to ship handling problems and navigational hazards within several miles from the coast. Collection of shallow water data is further compounded by political problems, especially in foreign areas. The optical ranges presented for each one-degree square will be slightly more turbid closer to the coast. It is extremely difficult to represent near-shore optical properties, since the local conditions (land/sea breeze, surf conditions, etc.) will strongly influence the optical climate.

The Secchi depth measurement is restrictive in clear water where the bottom can be seen. In areas where the bottom is readily visible (e.g., Bahamas, atolls) a Secchi range of 6 (> 25 m; purple) was used on the plates. The use of the Secchi depth measurement

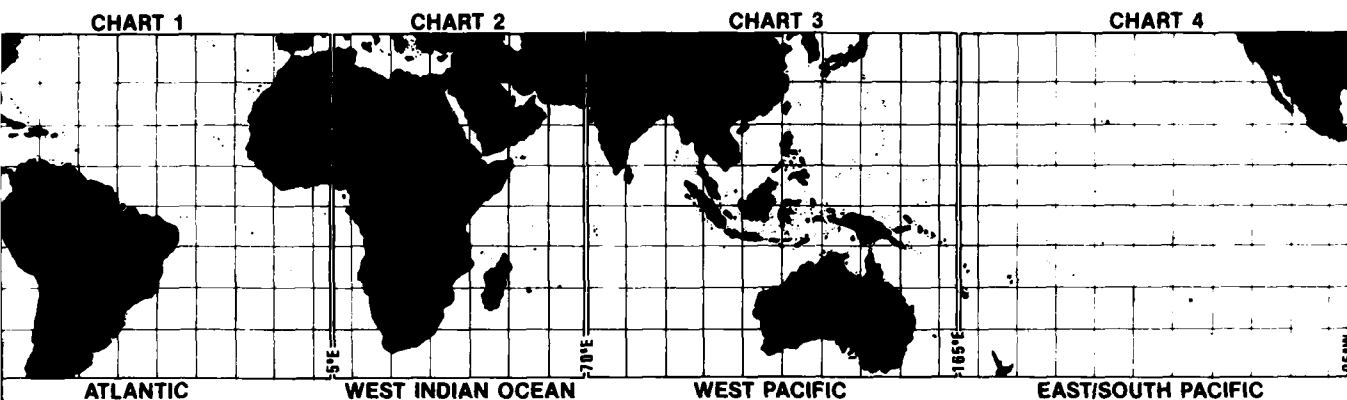


Figure 2. Geographical coverage for Charts 1-4.

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has this distinctive problem and suggests utilization of another op- tical property for future work.

## IV. Relationship of Secchi depths to water optical parameters

The Secchi depth is a rough measure of the water transparency in which a circular white disk, 43-237 cm in diameter, is lowered in the water and the depth at which it disappears from sight is observed. This measurement was first introduced in the 1865 cruise of the *Immaculate Concezione* in the Mediterranean (Cialdi and Secchi, 1968). Since then there have been attempts to standardize the procedures, although no consistent method is presently being used. Certain procedures indicate that the measurement should be done on the sun side of the ship, while others indicate the ship shadow side. The measurement is affected by both the solar elevation and the sea surface height (Hojerslev, 1974). The Secchi depth measurement is, to a certain extent, independent of the spectral characteristic of water because the human eye selects the optimum wavelength for maximum transparency when making the measurement. Different water masses have specific inherent characteristics by which a specific visible wavelength has maximum transmission. In clear ocean waters this wavelength occurs around 495 nanometers (nm) (blue-green), while in coastal waters a spectral shift toward 550 nm (brown) occurs (Fig. 3). The wavelength dependence of a water masses' maximum transmission coefficients is important for optical classifications (Jerlov, 1976). Similarly, this spectral dependence is characteristic of the biochemical properties.

Figure 4 indicates the range of Secchi depths for other types of optical parameters. Notice that the coastal water mass for harbors and estuaries has Secchi values of 1-3 m, which corresponds

to diffuse attenu- tion coefficient is is dependent on of measurement

$$k = -d [\ln (E$$

where  $E$  = irra

Therefore,  $k$  is logarithm of the tion coefficient downwelling radi of change for u (Austin and Petz wavelength depe

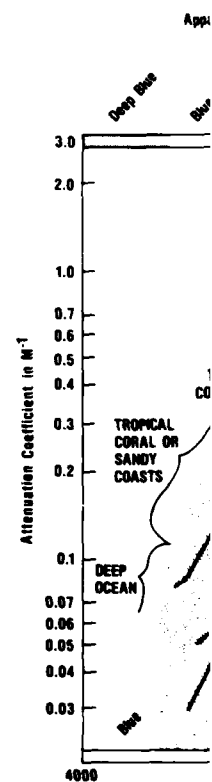


Figure 3. Spectral various water typ

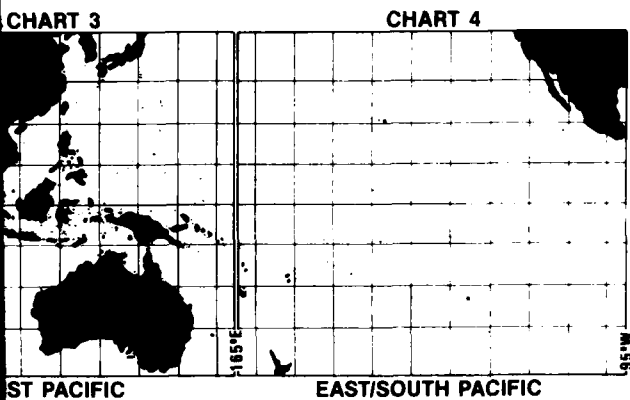


Figure for Charts 1-4.

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Figure 4 indicates the range of Secchi depths for other types of optical parameters. Notice that the coastal water mass for harbors and estuaries has Secchi values of 1-3 m, which corresponds

to diffuse attenuation coefficient values of 2-1. The diffuse attenuation coefficient is an apparent optical property in that its magnitude is dependent on the radiance distribution that exists at the point of measurement. The diffuse attenuation coefficient is defined as

$$k = -d [\ln (E_Z)] / dZ, \quad (1)$$

where  $E$  = irradiance at depth,  $Z$ .

Therefore,  $k$  is a measure of the rate of change (slope) of the logarithm of the irradiance or radiance depth profile. The attenuation coefficient is typically a measure of the rate of change for downwelling radiance,  $k_d$  into the water column, although the rate of change for upwelling radiance,  $k_u$ , can also be determined (Austin and Petzold, 1980). This attenuation coefficient is very much wavelength dependent as is shown in Figure 4.

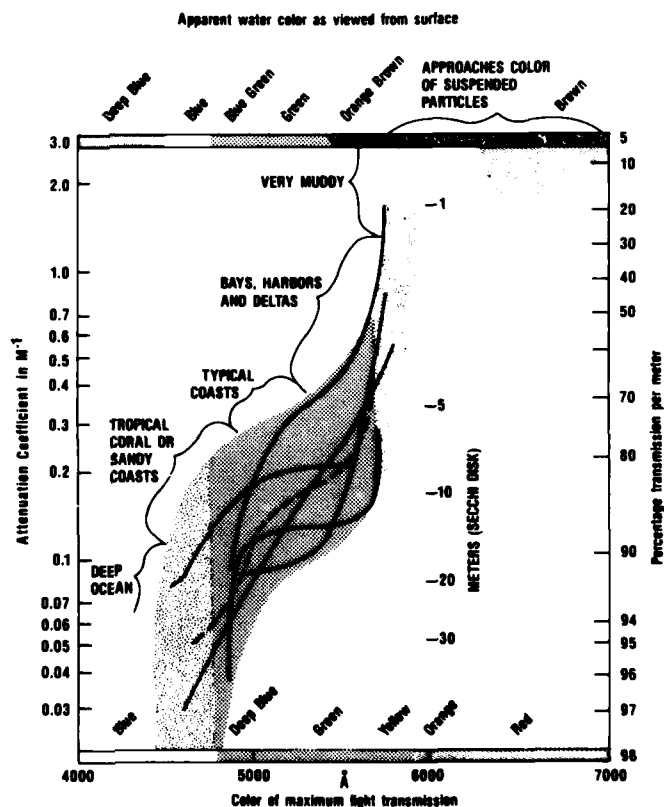
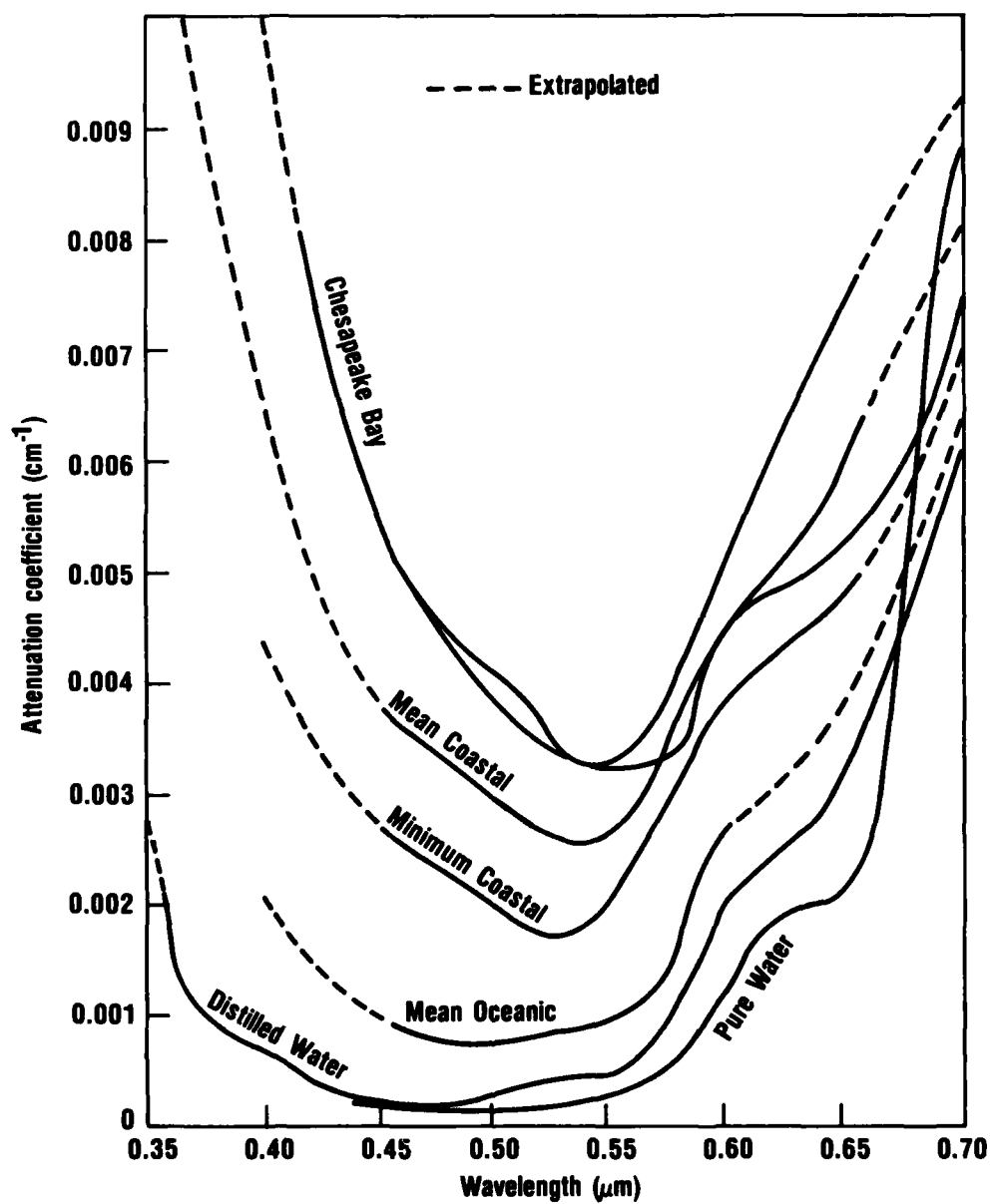
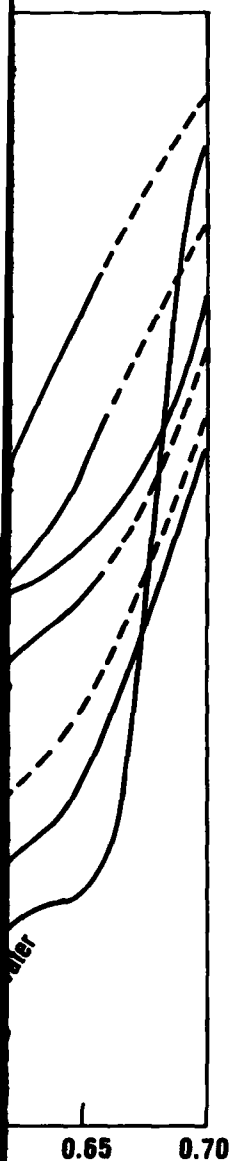


Figure 3. Spectral distribution of the attenuation coefficient for various water types.



Attenuation coefficients vs. wavelength (μm)

Figure 4. Spectral relationships of water optical properties and water color for various water types (Lepley, 1968).



Shannon (1975) has established an empirical relationship between the average diffuse attenuation coefficient and Secchi depth.

$$\bar{k} = 1.15 Z_s + 0.03 [m^{-1}] \quad (2)$$

where  $Z_s$  = Secchi depth.

$\bar{k}$  = average diffuse attenuation coefficient.

Additional relationships by other investigators can be found in Van Norden and Litts (1979).

The beam attenuation coefficient is an inherent, spectrally dependent optical property that characterizes the attenuation due to scattering and absorption in a collimated beam of monochromatic light across a fixed pathlength of homogeneous water. The measurement is a point measurement within the water column that, through a continuous depth profile, is used to describe vertical inhomogeneity of the water properties. The measurement obtains the percent transmission of the water column, which is then computed to beam attenuation coefficient by

$$C_\lambda = -\frac{1}{R} \ln \left( \frac{T_\lambda}{100} \right) \quad (3)$$

where  $C$  = beam attenuation coefficient at wavelength,  $\lambda$ .

$R$  = pathlength,

$T$  = percent transmission.

Shannon (1975) has suggested a relationship between  $C$  and  $\bar{k}$ , as follows:

$$\bar{k} = 0.2 C + 0.04 (m^{-1})$$

The optical properties of coastal waters and deep ocean waters are significantly different as a result of the biological and chemical processes that occur in each of these water types. The optical properties in deep ocean waters are influenced by the absorption characteristics of the phytoplankton population. In coastal areas high concentrations of suspended sediment have significant scattering and absorption influence on optical properties. Because of these two types of influence the correlation of water optic properties with the biochemical distribution becomes extremely complex (Arnold, 1983).

Gordon and Wounters (1978) have suggested that the use of the Secchi depth measurement provides significant information on the absorption and scattering coefficient of water when combined with additional measurements of  $k$  or scattering coefficients of the particles,  $b_p$ . Other studies in coastal waters have attempted to relate Secchi depth measurements to suspended sediment concentrations. It was found that this inverse relationship was strongly dependent on the size distributions of the suspended sediments. Manheim and

Mead (1970) indicated that the relationship:

$$Z_s = \frac{AdQ}{w}$$

where  $d$  = mean diameter,

$Q$  = density,

$w$  = weight of suspended,

$A$  = constant.

Other studies have related the nephelometric turbidity units (NTU)

## V. Environmental in Secchi depth

Several factors that have a direct relationship to Secchi depth values in coastal waters were used to estimate the Secchi depth for various regions of the world. As mentioned, the factors used are color, turbidity, and chlorophyll. The color is striped in the ocean.

### A. Phytoplankton

Chlorophyll, which is the pigment responsible for photosynthesis, is present in organisms called phytoplankton. Phytoplankton acidify chlorophyll components, chlorophyll a and b, and have been termed phytoplankton pigments. The absorption and scattering properties of phytoplankton from this point of view (Fig. 5), and some spectral characteristics are noted. However, about these wavelengths is believed to be the pigment.

There are vertical, seasonal, and diurnal variations in phytoplankton abundance. The vertical variation is determined by the depth of the euphotic zone. This depth may range from a few meters in shallow areas to about 150 m in deep areas. Variations in phytoplankton abundance occur as a consequence of temperature, mixing rate of the water, and the availability of nutrients (Si, Fe, Mn, Mo) and herbivore grazing within 24 hours, provided a



established an empirical relationship between attenuation coefficient and Secchi depth.

$$K [m^{-1}] \quad (2)$$

depth.

diffuse attenuation coefficient.

as by other investigators can be found in Van (1979).

on coefficient is an inherent, spectrally dependent that characterizes the attenuation due to scattering in a collimated beam of monochromatic light through a homogeneous water. The measurement is taken within the water column that, through a profile, is used to describe vertical inhomogeneities. The measurement obtains the percent water column, which is then computed to beam path by

$$\frac{K(\lambda)}{K(\lambda_0)} \quad (3)$$

attenuation coefficient at wavelength,  $\lambda$ ,  
depth,  
transmission.

suggested a relationship between  $C$  and  $\bar{k}$ , as

$$(m^{-1})$$

ties of coastal waters and deep ocean waters are different as a result of the biological and chemical differences in each of these water types. The optical properties of coastal waters are influenced by the absorption of phytoplankton population. In coastal areas with high suspended sediment have significant scattering influence on optical properties. Because of the influence the correlation of water optical properties and sediment distribution becomes extremely complex.

others (1978) have suggested that the use of measurement provides significant information on scattering coefficient of water when combined with measurements of  $\bar{k}$  or scattering coefficients of the sediments in coastal waters have attempted to relate measurements to suspended sediment concentrations. An inverse relationship was strongly dependent on the suspended sediments. Manheim and

Mead (1970) indicated that the Secchi depth had the following relationship:

$$Z_s = \frac{Ad\rho}{w} \quad (4)$$

where  $d$  = mean diameter,

$\rho$  = density,

$w$  = weight of suspended particles,

$A$  = constant.

Other studies have related the Secchi depths in coastal waters to nephelometric turbidity units (NTU) (Arnone, 1983).

## V. Environmental influence on coastal Secchi depth

Several factors that have a direct influence on the variability of Secchi depth values in coastal waters will be discussed. These factors were used to estimate the Secchi depth values in the one-degree squares for various regions of the atlas where Secchi data was not available. As mentioned, the inferred values obtained in this manner are color striped in the one-degree squares in the plates.

### A. Phytoplankton

Chlorophyll, which is the pigment present in living plants responsible for photosynthesis, is present in sea water in microscopic organisms called phytoplankton. Zooplankton feeding on phytoplankton acidify chlorophyll a to phaeopigments. These two components, chlorophyll a and phaeopigments of sea water, have been termed phytoplankton pigment concentration and have similar absorption and scattering properties in the visible spectrum. Strong radiance absorption from this pigment is observed at 440 and 665 nm (Fig. 5), and some spectral dependencies resulting from different species are noted. However, the intensity of the absorption about these wavelengths is believed to be related to the concentration of the pigment.

There are vertical, seasonal, and regional variations in phytoplankton abundance. The vertical distribution is influenced primarily by the depth of the euphotic zone in which photosynthesis can occur. This depth may range from less than a meter in turbid near-shore areas to about 150 m in clear oceanic waters. Seasonal oscillations in phytoplankton abundance, species composition and production occur as a consequence of a complex interacting of light, temperature, mixing rate of the water mass, plant nutrients (N, P, Si, Fe, Mn, Mo) and herbivore abundance. Growth rates can double within 24 hours, provided adequate conditions prevail. Limiting

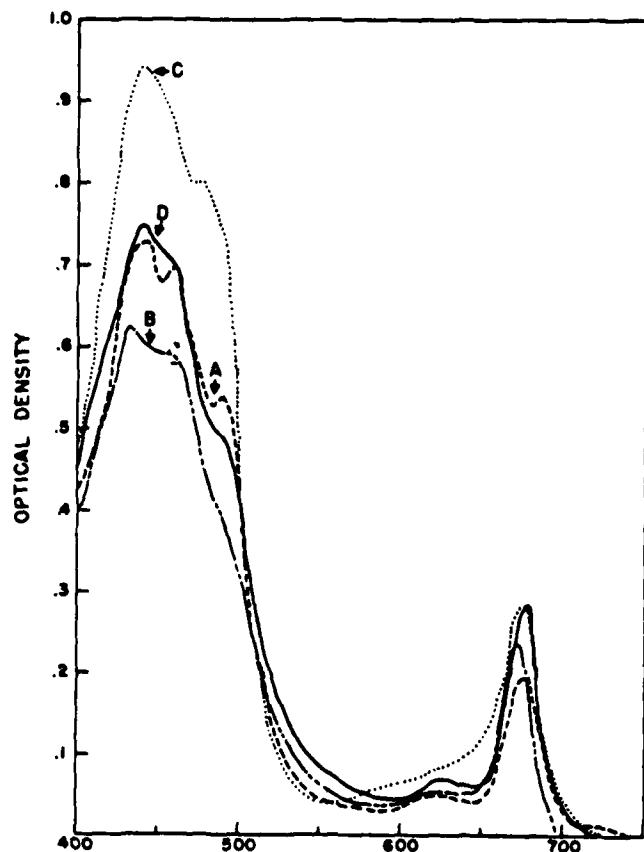


Figure 5. Absorption spectra of extracts of plankton algae: (A) a diatom, *Cyclotella* sp.; (B) a dinoflagellate, *Amphidinium* sp.; (C) a green flagellate, *Chlamydomonas*; (D) a natural population sampled from Woods Hole waters (from Yentsch, 1960).

factors of phytoplankton growth are inadequate illumination, excessive vertical mixing, nutrient limitation by extraction of Si and Fe through growth, and excessive grazing of zooplankton.

Regional variations in phytoplankton abundance, species distribution, and production also result from environmental conditions. Phytoplankton growth is stimulated in areas where two water masses diverge (equatorial Pacific and Norwegian Sea) or where upwelling of cool, nutrient-rich water reaches the surface from displacement of offshore winds (west coast of Africa, Central and South America).

The optical properties that result from phytoplankton are a product of both the absorption characteristics of the concentration and the scattering characteristics of the size distribution of the species.

Various theoretical optical models have been constructed to examine the optical properties of phytoplankton (Morel and Bricand, 1980; Yentsch, 1960). The results indicate that backscattering is weak but is strongly influenced by absorption, and that specific absorption (per unit of pigment concentration in the water) varies with cell size as well as intracellular pigment concentration.

Morel and Prieur (1977) have classified seawaters according to the constituents responsible for absorption and scattering. The influence of phytoplankton and their covarying detrital products is compared to inorganic and organic suspended particulates. Case 1 waters were classified as those whose optical properties are derived from the response of phytoplankton and its detrital products. Case 2 waters are classified as those whose optical properties result from inorganic and/or organic sediments arising from resuspended sediments, terrigenous particles, dissolved organic matter, and phytoplankton and associated detrital products.

Case 1 waters usually are associated with deep ocean water areas, although there are regions where Case 1 waters are present in coastal areas. Regional upwelling areas bordering coastal areas will contain Case 1 waters, which mix with inner-shelf, coastal-type Case 2 waters. Because of the strong relationship between the phytoplankton and optical properties, the term bio-optical properties has been associated with Case 1 waters.

Case 2 waters show high scattering from the interaction with the high concentrations of suspended particles as compared to Case 1 waters. Phytoplankton concentrations can be quite high in Case 2 waters, but they do not covary with the optical properties. Numerous cases have shown that Case 2 waters generated in coastal regions have been carried far offshore into the deeper oceanic waters. The spectral classification of the water optical properties results from the combined complex interaction of absorption, resulting from the phytoplankton, and scattering from the various size distributions of the particles. This combined interaction results in the ocean color. The strong absorption characteristics in the blue spectrum resulting from phytoplankton tend to result in greenish coloration of the water body. This water color is contrasted to a brown color resulting from increased scattering from suspended sediments. Methods of classifying water masses have been based on the spectral optical properties (ocean color), which distinctly define the interrelationships of the absorption and scattering properties of the water mass constituents.

## B. Proximity to river discharge

A major influence on water optical variability in coastal areas is the proximity to river discharge. The increased concentrations of suspended sediments and dissolved organic material resulting from river discharge have significant effects on scattering and ab-

theoretical optical models have been constructed to explain optical properties of phytoplankton. (Morel and Bricand, 1960). The results indicate that backscattering is strongly influenced by absorption, and that specific (per unit of pigment concentration in the water) varies as well as intracellular pigment concentration. and Prieur (1977) have classified seawaters according to components responsible for absorption and scattering. The in- phytoplankton and their covarying detrital products is to inorganic and organic suspended particulates. Case are classified as those whose optical properties are derived response of phytoplankton and its detrital products. Case are classified as those whose optical properties result from and/or organic sediments arising from resuspended terrigenous particles, dissolved organic matter, and phytoplankton and associated detrital products.

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## Proximity to river discharge

The influence on water optical variability in coastal areas is directly related to proximity to river discharge. The increased concentrations of suspended sediments and dissolved organic material resulting from river discharge have significant effects on scattering and ab-

sorption of coastal optical properties. These properties are indirectly the result of the drainage basin of the river.

The drainage basin's size, type of terrain, and composition of the soil ultimately influence the water optical properties. A large drainage basin in a low-lying, clayey soil usually will have river waters that contain a high concentration of suspended sediments with a small size distribution and slow-settling velocities. Thus, at the river discharge point the optical environment will be significantly influenced by turbid water conditions for a large surrounding area. The slow dissipation of the discharge plume will be influenced by local circulation patterns that could affect coastal areas along an entire coastal region. Higher energy drainage basins (e.g., Colorado River), typical in mountainous (tectonic) regions, contain larger-sized particles in suspension. The discharge of these type rivers is more localized at the river mouth, since these particles will settle out of solution rapidly. Drainage basins in low-lying, organically rich environments emit high concentrations of dissolved organic material to the coastal environment. Heavy rains during flood seasons flush the swamp of decaying organic material and produce large concentrations of humic and tannic acid in the river waters (referred to as a yellow substance or dissolved organic matter). The tea-colored Suwannee River, which drains Georgia's Okefenokee swamp, is an example. Upon entering the coastal environment this material is diluted with sea waters and responds to the local circulation patterns. Thus, the dynamic turbulence mixing that occurs at the river mouth determines the influence of the distribution of yellow substance in the overall coastal optical environment. Dissolved organic material is responsible for strong absorption of radiation especially in the shorter wavelengths.

In coastal areas where a significantly large discharge of suspended sediment is introduced into the environment, the optical properties show a covarying response. Instances where this occurs result in suspended sediment concentrations greater than 100 mg/l. In these instances the phytoplankton growth response is inhibited by the reduced light levels that result from the suspended sediment load. Thus, the optical properties are dominated by the response of the suspended sediment concentration. Coastal areas where these conditions arise are located at major river mouths. Table 1 lists the 21 major rivers of the world and their corresponding sediment discharge rates.

Figure 6 illustrates the annual discharge rates for various regions of the world (Milliman and Meade, 1983). The significance of this figure in regard to coastal properties is that it indicates regions where suspended sediments from river emission are important. Through correlation of this figure with local coastal currents the distribution of the sediment pattern in the near shore can be established. This figure should be contrasted to results of the Secchi values shown in the plates. The optical values in proximity to the river mouths are observed to be reduced.

Table 1. Quality of discharges to the

River
1. Ganges Brahmaputra
2. Yellow (Hwang)
3. Amazon
4. Yangtze
5. Irrawaddy
6. Magdalena
7. Mississippi
8. Orinoco
9. Hungho (Red)
10. Mekong
11. Indus
12. MacKenzie
13. Godavari
14. La Plata
15. Haiho
16. Purari
17. Zhu Jiang (Pearl)
18. Copper
19. Danube
20. Choshui
21. Yukon

The coastal optical properties are directly influenced by the seasonal discharge rates available on a limited

## C. Tides

The importance of tides on coastal optical properties arises primarily from the mixing caused by tidal currents in local regions where the water is affected by coastline conditions. In these areas, high tidal velocities tend to resuspend sediments. The resuspension is dependent on the sediment composition, density, and additional information on the local environment where the suspended sediments remain in suspension. The sediment concentrations are affected by the tide. Constant tidal velocities in extremely turbid waters tend to maintain the global range in sediment concentrations to determine the effects of the optical properties from this

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Table 1. Quality of data base for 21 largest river-sediment  
discharges to the ocean (Milliman and Meade, 1983).

River	Average Sediment Discharge ( $10^6$ t/yr)	Adequacy of Data Base
1. Ganges/Brahmaputra	1670	Inadequate
2. Yellow (Hwang)	1080	Good
3. Amazon	900	Inadequate
4. Yangtze	478	Good
5. Irrawaddy	285	Inadequate(?)
6. Magdalena	220	Inadequate
7. Mississippi	210	Good
8. Orinoco	210	Sufficient
9. Hungo (Red)	160	Inadequate
10. Mekong	160	Sufficient
11. Indus	100	Sufficient
12. MacKenzie	100	Poor to Fair
13. Godavari	96	Inadequate
14. La Plata	92	Inadequate to Sufficient
15. Haiho	81	Good
16. Purari	80	Inadequate
17. Zhu Jiang (Pearl)	69	Sufficient to Good
18. Copper	70	Sufficient
19. Danube	67	Good
20. Choshui	66	Sufficient
21. Yukon	60	Sufficient

The coastal optical conditions resulting from river discharge are  
directly influenced by the seasonal run-off patterns of the river basin.  
The seasonal discharge of suspended sediments of major rivers is  
available on a limited basis.

### C. Tides

The importance of tidal influence on coastal water optical prop-  
erties arises primarily from the resuspension of bottom material  
caused by tidal currents. This influence is extremely important in  
local regions where significantly high tidal ranges are restricted  
by coastline conditions (i.e., Bay of Fundy, English Channel). In  
these areas, high tidal currents are capable of reaching the critical  
velocity to resuspend bottom material. The critical velocity for  
resuspension is dependent on the bottom type (i.e., size distribu-  
tion, composition, density, shear strength, porosity, etc.). For ad-  
ditional information see Miller et al. (1977). In coastal conditions  
where the suspended particles have slow settling velocities, such  
that they remain in suspension during slack tide, the suspended  
sediment concentration remains quite high during all stages of the  
tide. Constant tidal reversals in coastal regions can result in ex-  
tremely turbid water conditions at all times. Figure 7 illustrates  
the global range in tides in coastal areas. Although it is difficult  
to determine the effect that these ranges have on coastal optical  
properties from this figure alone, by correlating these tidal ranges

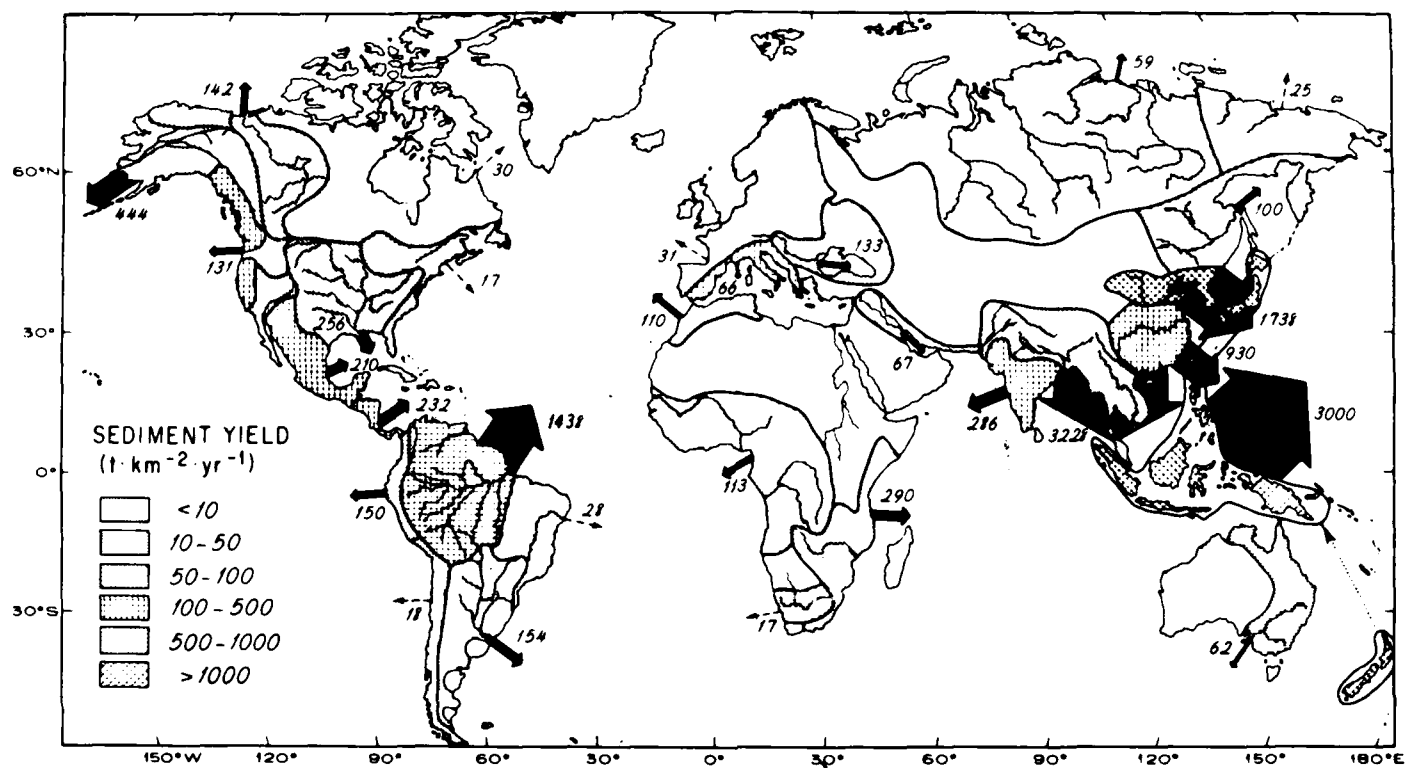


Figure 6. Annual discharge of suspended sediment from various drainage basins of the world; width of arrows corresponds to relative discharge. Numbers refer to average annual input in millions of tons. Direction of arrows does not indicate direction of sediment movement. The sediment yields and major rivers of the various basins also are shown; open patterns indicate essentially no discharge to the ocean (Milliman and Mead, 1983).

with local geomorphology, bathymetry and bottom type, an estimate of the tidal influence on optical conditions can be realized. Areas with high tidal ranges are expected to have more turbid coastal properties than for small tidal ranges.

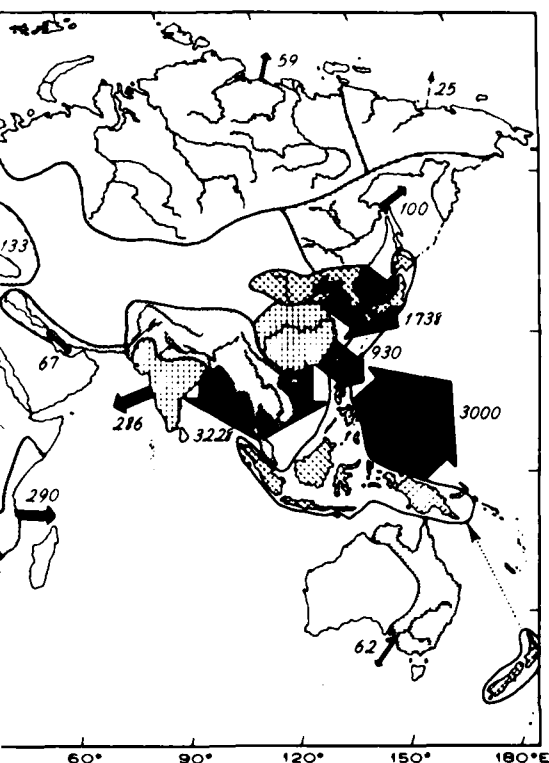
#### D. Offshore currents

The distribution of coastal optical properties can be influenced by offshore currents. Figure 8 illustrates the major ocean currents in the oceans. The westward boundary currents (Gulf Stream, Kuroshio) are significantly strong and can have significant influence on the near-shore circulation and distribution of optical properties. The influence of ocean currents in coastal areas is more pronounced if the continental shelf is narrow and the clearer ocean waters are able to extend closer to the coast. The direction of the offshore currents provides an indication of the transport direction of coastal water masses. The discharge of the Amazon River is transported by the effects of the Guiana current to the northwest;

thus, the coastal optical properties are significantly different than to the southeast of the Amazon delta. Similarly, coastal optical properties can be estimated along the west African coast at the convergence of the Canary current and the Benguela current. Increased water turbidity is expected, as resulting from transport of nutrient-rich coastal water and consequent bloom of phytoplankton.

The seasonal variation in ocean currents should be noted to also create seasonal changes in the distribution of coastal optical values. The effect of the monsoons has significant effects on the east African coastal current (Somali current). During the winter months this current flows south, whereas the current is shown to flow north during the monsoon. The influence on coastal water mass transport has not been adequately researched although the seasonal variability of coastal optics is evident.

Most ocean current waters are characterized by clear water optical properties having low phytoplankton concentrations (i.e., Gulf Stream, Loop Current). However, at the current boundaries where



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ties having low phytoplankton concentrations (i.e., Gulf  
p Current). However, at the current boundaries where

ocean fronts occur, numerous chemical, biological, and physical  
processes produce increased water turbidity. The ocean frontal zones  
are an extremely complex current shear area in which instabilities  
in the flow give rise to spin-off rings. The movements of spin-off  
rings and ocean frontal areas are presently under investigation, as  
is their physical and biological effect on coastal optics waters.

From a biochemical point of view, frontal areas can be viewed  
as giant chemical reactors fueled by components supplied via water  
mass transport, with the resultant chemical reactions biologically  
radiated by photosynthesis, respiration, and microbial degradation.  
Chemical, biological, and physical processes are being studied to  
characterize the spatial and temporal variability of the frontal regime  
in regard to optical properties. Fronts are recognized on large-scale  
ocean fronts and on a small scale as coastal fronts. Similar response  
of the optical properties is expected.

### E. Meteorology

Local meteorology has a significant influence on the local coastal  
waters. Specific regions have certain types of local meteorology that  
directly influence the land/water boundary conditions. For exam-  
ple, the typical land/sea breeze pattern typical of summer low-latitude  
areas influences the coastal optical properties. The afternoon thunder-  
showers, which result from this climatic pattern, produce fresh-  
water runoff and increased wave conditions that ultimately increase  
the water turbidity. For this regime, early morning conditions are

perhaps the best to  
at a minimum and  
to settle.

Frontal passages  
passage of cold front  
and heavy rains (dep  
results in turbulent  
sion of bottom sedi  
water turbidity will  
The time required f  
to clear depends on  
generated by tides.  
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Figure 7. Tidal range along the coasts of the world.

its occur, numerous chemical, biological, and physical produce increased water turbidity. The ocean frontal zones extremely complex current shear area in which instabilities give rise to spin-off rings. The movements of spin-off ocean frontal areas are presently under investigation, as physical and biological effect on coastal optics waters. From a biochemical point of view, frontal areas can be viewed as chemical reactors fueled by components supplied via water transport, with the resultant chemical reactions biologically photosynthesis, respiration, and microbial degradation. Biological, and physical processes are being studied to determine the spatial and temporal variability of the frontal regime and optical properties. Fronts are recognized on large-scale maps and on a small scale as coastal fronts. Similar response optical properties is expected.

## Meteorology

Meteorology has a significant influence on the local coastal optical properties. Specific regions have certain types of local meteorology that influence the land/water boundary conditions. For example, the land/sea breeze pattern typical of summer low-latitude regions influences the coastal optical properties. The afternoon thunderstorms which result from this climatic pattern, produce freshening and increased wave conditions that ultimately increase turbidity. For this regime, early morning conditions are

perhaps the best for clear water conditions, since the winds are at a minimum and the suspended coastal particulates have had time to settle.

Frontal passages are often common in many coastal areas. The passage of cold frontal systems usually has associated strong winds and heavy rains (dependent on the severity of the front). This passage results in turbulent mixing of the upper water column and resuspension of bottom sediment material in the near-shore areas. Resulting water turbidity will be severely increased in these localized areas. The time required for the particulates to settle out and the waters to clear depends on the particle size and density, and the turbulence generated by tides, etc. It is common for a period of 3-4 days to elapse with extremely calm sea and wind conditions before the water clarity returns to normal conditions. Clear water conditions (i.e., the Bahamas) can become extremely turbid with the passage of a cold front or a severe storm within several hours. The resulting turbid water conditions can persist for 5 days before clear waters return. The passage of fronts in many instances is followed by a cold, stable, high-pressure area in which the winds are somewhat reduced. Although these conditions appear excellent for coastal water optics, it can require several days of this condition before the water clarity improves.

As indicated, the coastal oceanographic climate is significantly different for specific regions. Although the present atlas has been compiled into four seasons (winter, spring, summer, fall), certain

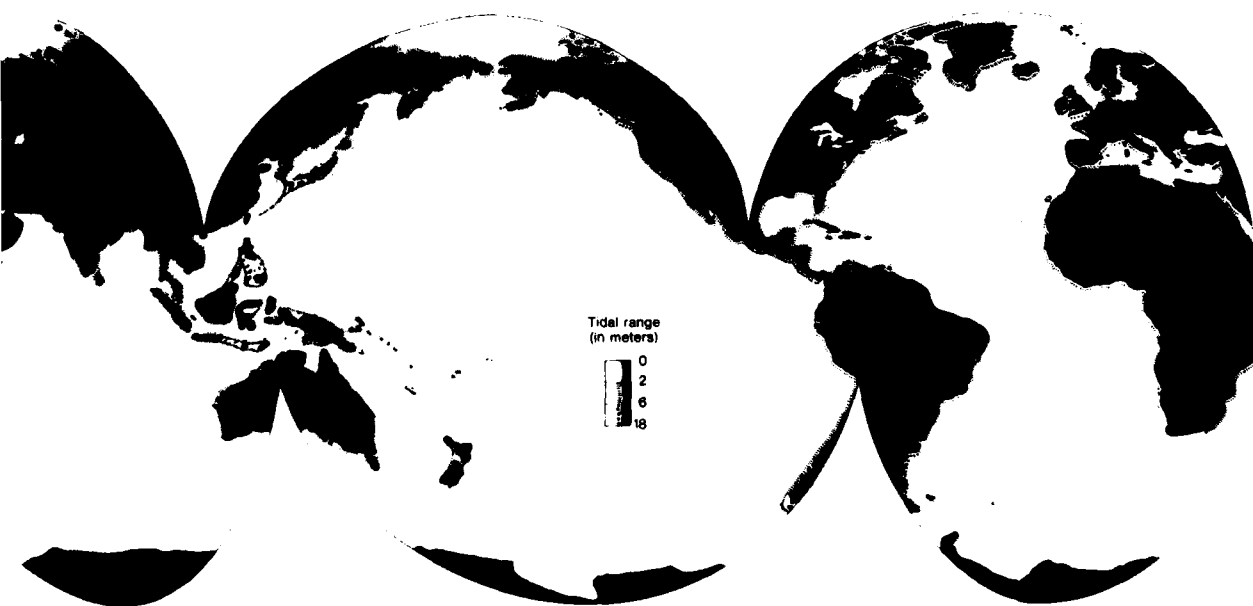


Figure 7. Tidal range along the coasts of the world.

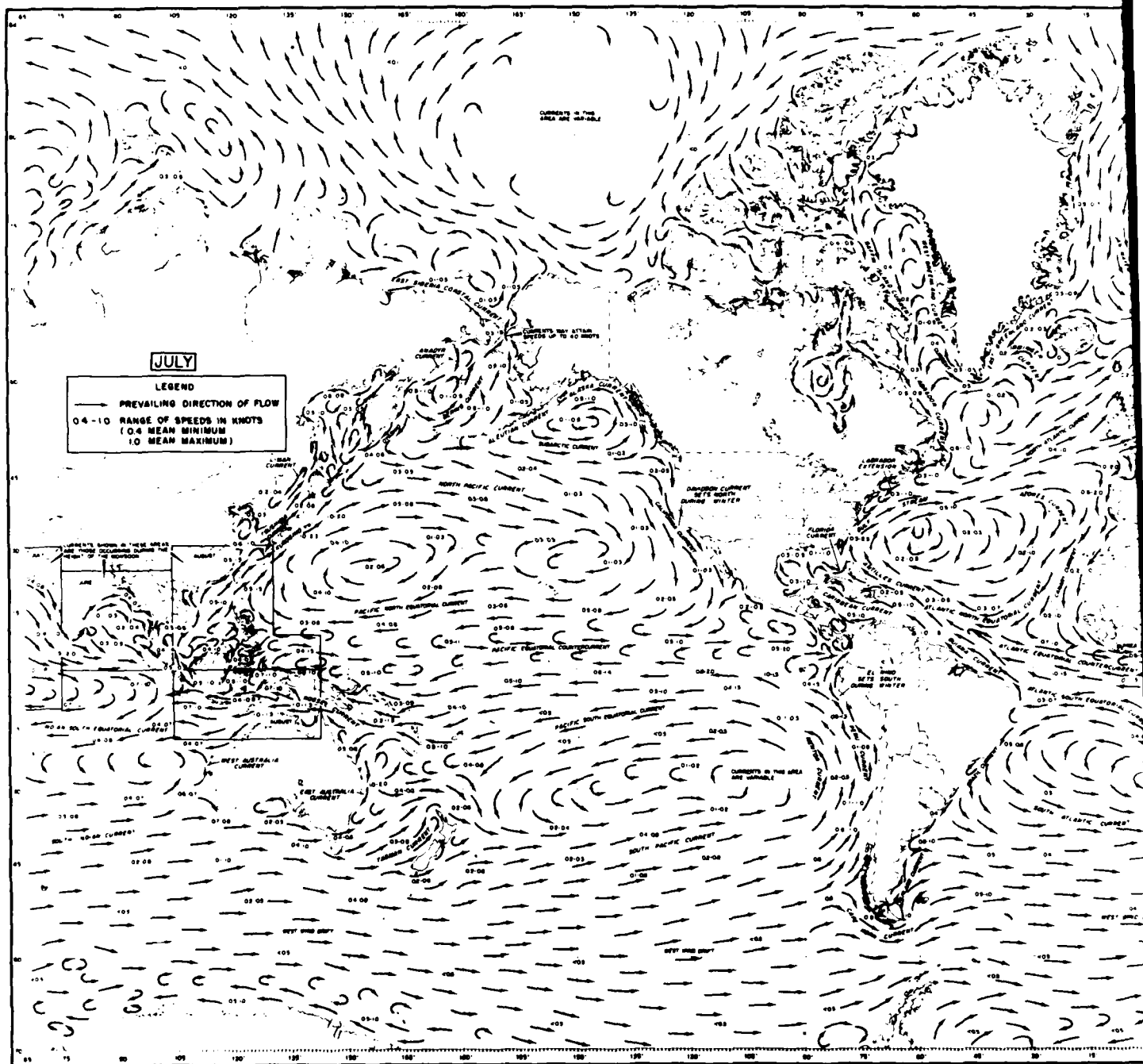
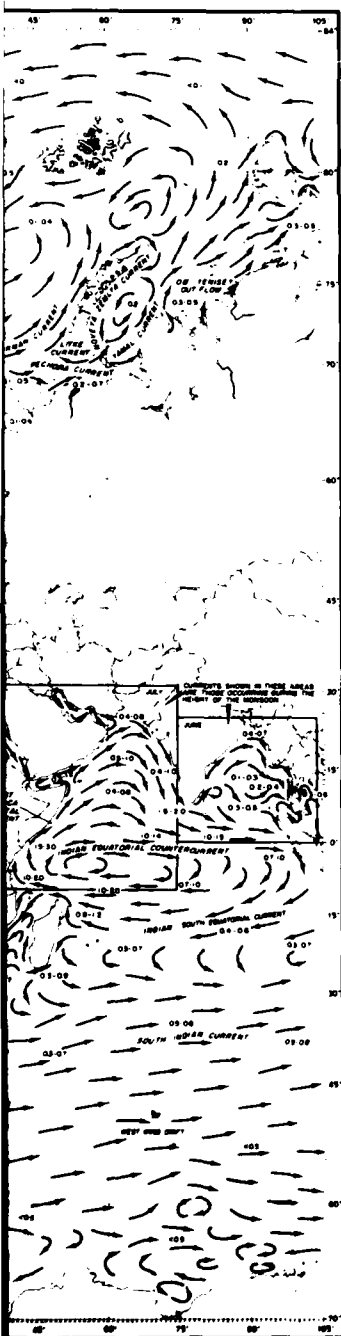


Figure 8. World ocean currents for July (Bialek, 1966).







regions have significantly different seasons. The monsoon season, which occurs in the Indian Ocean, has four distinct seasons: the northeast monsoon (Dec-Mar), the interperiod (Apr-May), the summer monsoon (Jun-Sep), and the fall interperiod. Figure 9 illustrates the monthly progression of the wind and rain pattern in the northern Indian Ocean. The strong onshore winds during the June and July period result in high wave conditions, and the coastal clarity is reduced. This is compounded by heavy rains during these months. The offshore wind patterns along the west Indian coast result in decreased coastal fetch and decreased coastal waves. The winter months are, therefore, most probable for clear coastal waters in this region.

## F. Coastal geomorphology

The basic geologic coastal landforms influence the coastal optical properties. The classification of the coastline is dependent on the soil composition, geomorphic conditions, beach stability, and tectonic activity. For a chart of coastal landforms, see McGill (1958). In many instances the general coastal classification can be utilized as an influence on the coastal optical properties. For example, a proceeding coastline that is being developed by sedimentary deposits of clay will most likely have large concentrations of fine-sized particles within the water column. Their slow-settling velocity, combined with the high sediment input to the coastal area, results in turbid coastal waters.

## VI. Results

The results of the color-coded atlas are illustrated in Plates 1-20. The annual mean for Chart 1 is illustrated, followed by Seasons 1-4. This sequence is followed for Charts 2, 3, and 4. The blocky one-degree squares are clearly observed along the coastal areas. In the areas where ranges were estimated, the area has been striped in by the appropriate color code. The annual mean charts (Plates 1, 6, 11, 16) contain the most data, as shown by the large amount of solid one-degree squares. The seasonal charts have sufficiently less data available, and additional Secchi depth estimates were required.

The spatial variability characterized by these figures illustrates the rapidly changing coastal optics. Notice that the Malacca Strait (Chart 3, Plate 11) is quite turbid and that approximately 200 nautical miles (NM) to the northeast, waters are extremely clear. Similar high spatial variability is observed near the Gulf of Tonkin. This high variability is perhaps more striking than might be estimated, since the data has been averaged over one-degree squares and overall seasons. This procedure should filter out the high frequency variability. The existing high variability suggests that more data are required to determine whether the temporal or spatial variability is more prevalent.

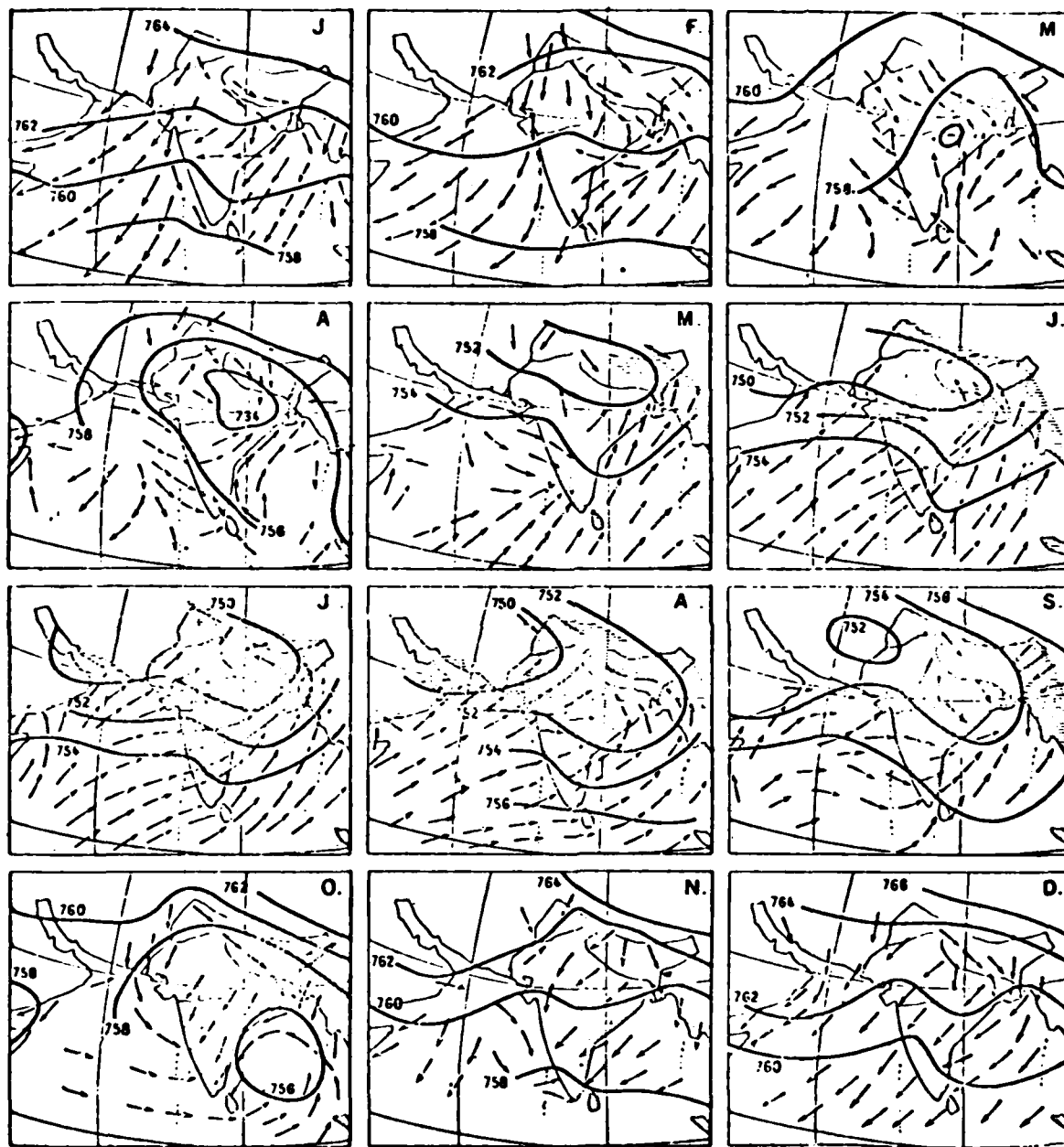


Figure 9. Annual evolution of the wind and pressure systems over the northern Indian Ocean from January to December. Rainfall areas are shaded (from de Martonne, 1950). (750 mm = 1000 mb; 760 mm = 1013 mb)

The positions of the equatorial oceanic and coastal currents are observed to affect the coastal optical properties in such areas as the west African and west South American coasts. Discharge of major rivers is also observed to control the seasonal coastal turbidity along long coastlines.

To characterize the general water turbidity ranges for global coverage and to estimate the seasonal trends, the number of one-degree squares for each Secchi depth range for each chart was counted to establish the seasonal variability for the coastlines.

The results of this analysis are illustrated in Figure 10 and tabulated in Tables 2-6. It should be noted that the four charts have unequal numbers of one-degree squares bordering coastlines. The percentage of coastline (water depths less than 500 m) for each chart follows: Chart 1—25%; Chart 2—19%; Chart 3—45%; Chart 4—13%.

Figure 10a illustrates coastal coverage for each season for Chart 1 for each Secchi depth range. Chart 1 contains mostly the waters bordering the Atlantic Ocean. Range-1 (<5 m) is observed to have a slightly higher percentage in October-March than in the other months. The variability in this percentage can be attributed to the seasonal outflow of the Amazon River, whose discharge affects a large coastal area along northern South America. Although this percentage range is quite small (~6%), it is slightly higher than for the global average, as will be shown below. Range-2 shows a seasonal distribution similar to that for range-1. Range-4 is observed to contain the highest percentage of this chart, with a mean percentage of 31%. Ranges-5 and -6 do not indicate high seasonal variability. The percentage of very clear waters (range-6) is 21%, which is quite high compared to all continental coastal areas covered by this chart.

Figure 10b illustrates the percentage estin chart covers the western Indian Ocean, so and Red Sea areas. A significant change is sion with the previous chart in that the p water is reduced to approximately 1%. Th observed to occur in the July-September peri water comprises about 39%. Elevated coas in the October-December period, most like ly flow of the Somali current along the Af of the monsoon.

Figure 10c illustrates percentage estimates includes the largest coastal borders in the wor high percentage of range-1 waters is found. The seasonal distribution indicates that the J has the highest percentage of clear water distribution is observed for range-2 waters. R. show very little seasonal variability. A relat distribution is observed between ranges-5

Figure 10d illustrates percentage estimates Pacific in Chart 4. This area of coastal cov numerous atolls, yet it represents only 13 coastlines. The percentage of turbid range- siderably lower in this area, and range-6 wat of the coastal water in this area.

Figure 10e illustrates the global coastal p a composite of all four charts. The season coastal areas indicates that the July-Septem clearer water conditions than for the other t is attributed to the influence of the monsoon indicated on charts 2 and 3 estimates whe tions were observed during the October-M



the equatorial oceanic and coastal currents are the coastal optical properties in such areas as the west South American coasts. Discharge of water is observed to control the seasonal coastal turbidities.

The general water turbidity ranges for global waters estimate the seasonal trends, the number of one-degree squares for each chart was determined by the seasonal variability for the coastlines.

The results of this analysis are illustrated in Figure 10 and Figures 2-6. It should be noted that the four charts show the percentage of one-degree squares bordering coastlines. The percentage of coastal coverage (water depths less than 500 m) for each chart is: Chart 1—25%; Chart 2—19%; Chart 3—45%; Chart

Chart 4—13%. The percentage of coastal coverage for each season for Chart 1 is shown in Figure 10a. Chart 1 contains mostly the waters of the Atlantic Ocean. Range-1 (< 5 m) is observed to have a higher percentage in October-March than in the other seasons. The variability in this percentage can be attributed to the seasonal flow of the Amazon River, whose discharge affects the coastal area along northern South America. Although the percentage is quite small (~6%), it is slightly higher in the summer months. Range-2 shows a similar distribution, as will be shown below. Range-4 is observed to have the highest percentage of this chart, with a mean of 15%. Ranges-5 and -6 do not indicate high seasonal variability. The percentage of very clear waters (range-6) is 21%, compared to all continental coastal areas covered

Figure 10b illustrates the percentage estimates for Chart 2. This chart covers the western Indian Ocean, southern African coast, and Red Sea areas. A significant change is observed by comparison with the previous chart in that the percentages of range-1 water is reduced to approximately 1%. The clear water range is observed to occur in the July-September period, where the range-6 water comprises about 39%. Elevated coastal turbidity is shown in the October-December period, most likely because of southerly flow of the Somali current along the African coast as a result of the monsoon.

Figure 10c illustrates percentage estimates for Chart 3. This chart includes the largest coastal borders in the world (45%). A relatively high percentage of range-1 waters is found along the coasts (5%). The seasonal distribution indicates that the July-September period has the highest percentage of clear waters. A similar seasonal distribution is observed for range-2 waters. Ranges-3 and -4 waters show very little seasonal variability. A relatively similar seasonal distribution is observed between ranges-5 and -6.

Figure 10d illustrates percentage estimates for the East and South Pacific in Chart 4. This area of coastal coverage is composed of numerous atolls, yet it represents only 13% of the total world coastlines. The percentage of turbid range-1 or -2 waters is considerably lower in this area, and range-6 water occupies about 66% of the coastal water in this area.

Figure 10e illustrates the global coastal percentage taken from a composite of all four charts. The seasonal distribution for the coastal areas indicates that the July-September period has slightly clearer water conditions than for the other times. This seasonality is attributed to the influence of the monsoon seasons, which were indicated on charts 2 and 3 estimates where more turbid conditions were observed during the October-March period.

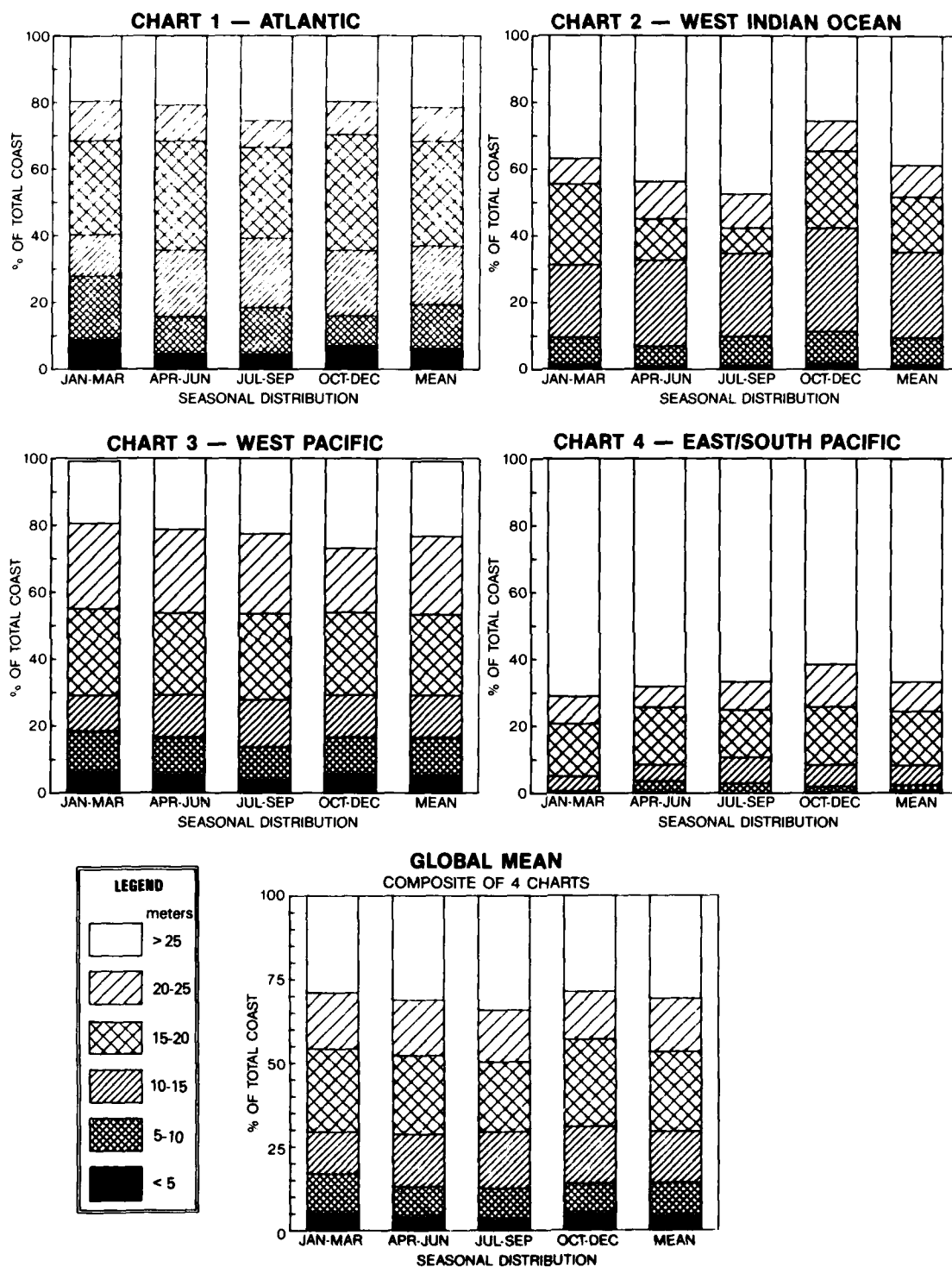


Figure 10. Seasonal and annual distribution of the percentage of Secchi depth ranges.

MEAN

Group	Mean
Control	~100
100 mg/kg	~85
200 mg/kg	~75

MEAN

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Secchi Depth Range	Season		
	1	2	3
1	4.98	3.76	2.94
2	11.91	9.19	9.59
3	12.50	15.73	16.88
4	24.80	23.46	20.94
5	16.78	16.64	15.48
6	29.01	31.19	34.16
Total # of squares	10,833		

A seasonal Secchi depth atlas of global condition has been compiled on 20 charts from a limited amount of data. Six ranges of values have been assigned to the charts. The first range is for waters less than 60 NM square and less than 500 m deep. The atlas illustrates a high coastal spatial and temporal variability in Secchi depth. Possible mechanisms for the variability are suggested. Modeling the optical variability with coastal processes is a future investigation and high-resolution data.

The global distribution of coastal Secchi depth is shown on the charts. The percentage of relatively clear waters. Less than 5% are shown to have less than 5 m Secchi depth values. The percentage of each range were observed in the percentage of coastal waters occurred in ranges: 0-5 m (< 5%), 5-10 m (5-10%), 10-15 m (10-15%), 15-20 m (15-20%), 20-25 m (20-25%), 25-30 m (25-30%), 30-35 m (30-35%), 35-40 m (35-40%), 40-45 m (40-45%), 45-50 m (45-50%), 50-55 m (50-55%), 55-60 m (55-60%), 60-65 m (60-65%), 65-70 m (65-70%), 70-75 m (70-75%), 75-80 m (75-80%), 80-85 m (80-85%), 85-90 m (85-90%), 90-95 m (90-95%), 95-100 m (95-100%).

Application of remote sensing technology for a digital data base has significant advantages in addition to temporal coverage. Presently, a regional study using a Zone Color Scanner aboard the Nimbus 7 satellite and an optical data base is nearing completion, and the results are encouraging.

—Percentage of one-degree squares.

	Season			Annual Mean
	2	3	4	
70	4.63	4.53	6.96	6.17
18	11.10	13.90	9.03	13.16
43	19.94	20.78	19.55	17.46
24	32.72	27.18	34.66	31.25
30	10.81	7.96	9.92	10.23
53	20.78	25.62	19.85	21.79
0				

—Percentage of one-degree squares.

	Season			Annual Mean
	2	3	4	
35	0.79	1.11	1.71	1.23
14	5.97	8.69	9.62	8.09
70	25.70	24.77	31.00	25.65
22	12.35	7.58	23.07	16.57
56	11.15	10.17	8.97	9.47
01	44.02	47.70	25.64	38.97
7				

—Percentage of one-degree squares.

	Season			Annual Mean
	2	3	4	
15	5.43	3.84	5.60	5.25
15	11.09	9.80	10.95	11.23
67	12.65	14.22	12.63	12.56
88	24.52	25.65	24.67	24.16
53	24.98	23.94	19.23	23.44
62	21.33	22.55	26.92	22.35
10				

—Percentage of one-degree squares.

	Season			Annual Mean
	2	3	4	
00	0.27	0.00	0.32	0.14
06	3.25	2.90	1.62	2.19
40	4.87	7.65	6.51	5.92
71	7.07	14.24	17.26	16.10
20	6.23	8.44	12.70	8.78
10	68.29	66.75	61.56	66.83
16				

Table 6. Global coverage—Percentage of one-degree squares.

Secchi Depth Range	Season				Annual Mean
	1	2	3	4	
1	4.98	3.76	2.94	4.66	4.07
2	11.91	9.19	9.59	9.17	9.96
3	12.50	15.73	16.88	16.97	15.33
4	24.80	23.46	20.94	26.14	23.85
5	16.78	16.64	15.48	14.32	15.86
6	29.01	31.19	34.16	28.72	30.92
Total # of squares 10,833					

## VII. Summary and conclusions

A seasonal Secchi depth atlas of global conditions ( $\pm 40^\circ$  latitude) has been compiled on 20 charts from a limited amount of available data. Six ranges of values have been assigned to coastal areas that are 60 NM square and less than 500 m deep. This limited data base illustrates a high coastal spatial and temporal variability. Probable mechanisms for the variability are suggested, although detailed modeling the optical variability with coastal processes requires additional investigation and high-resolution data.

The global distribution of coastal Secchi depths indicates a high percentage of relatively clear waters. Less than 5% of the coastlines are shown to have less than 5 m Secchi depth values. Little seasonal changes in the percentage of each range were observed. The highest percentage of coastal waters occurred in ranges-4 (15-20 m) and -6 ( $> 25$  m).

Insufficient spatial and temporal data in coastal areas was considered the most significant problem with atlas development. Improvements of the data base require that synoptic and improved spatial coverage be considered. Since field programs are man and cost intensive, the applications of visible remote sensing systems should be investigated for data collection. Only in this way can the spatial and temporal variability of the coastal optical properties be established for modeling purposes.

Application of remote sensing technology for generating an optical data base has significant advantages in addition to providing temporal coverage. Presently, a regional study using the Coastal Zone Color Scanner aboard the Nimbus 7 satellite for computing an optical data base is nearing completion, and the results are very encouraging.



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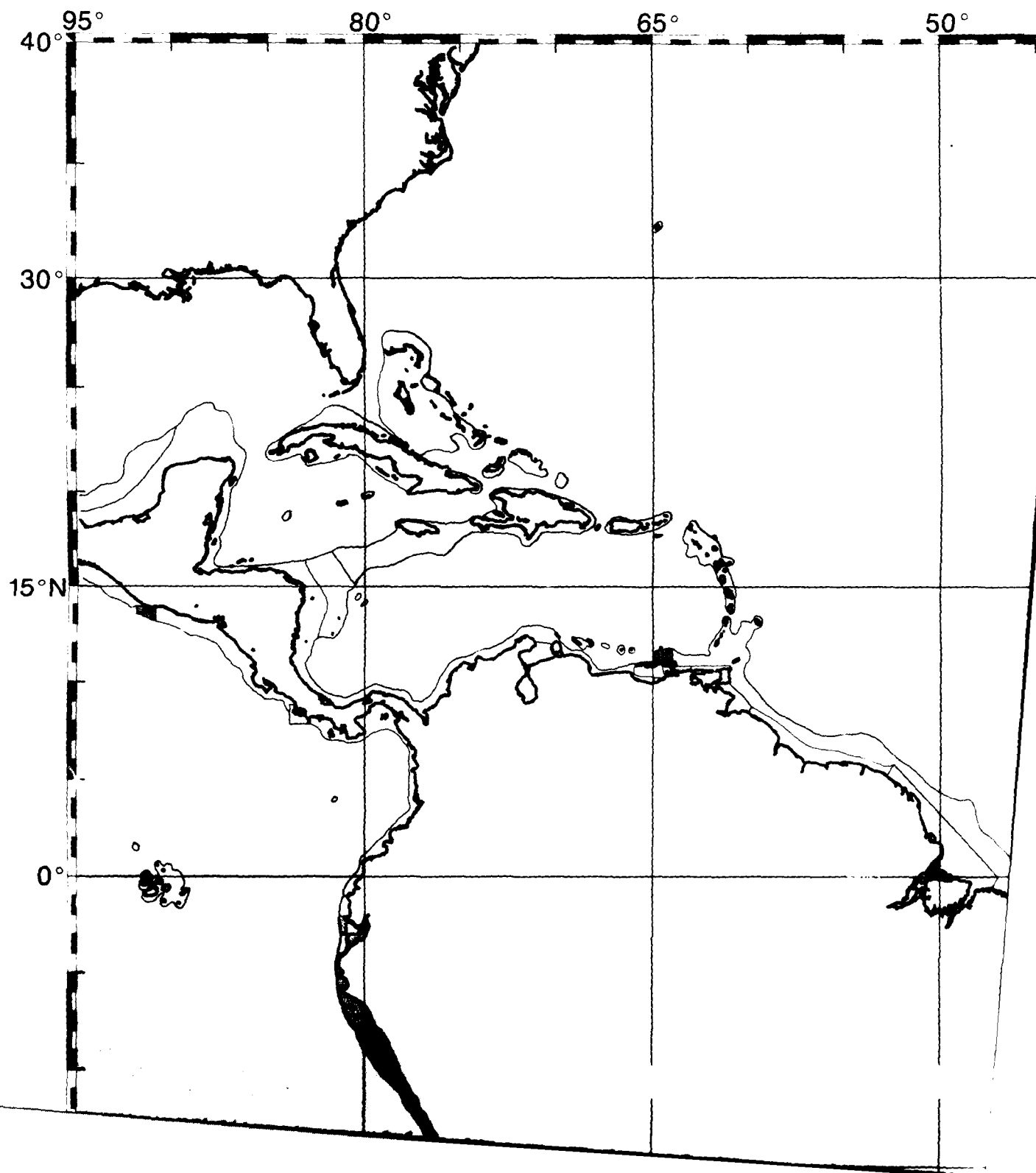
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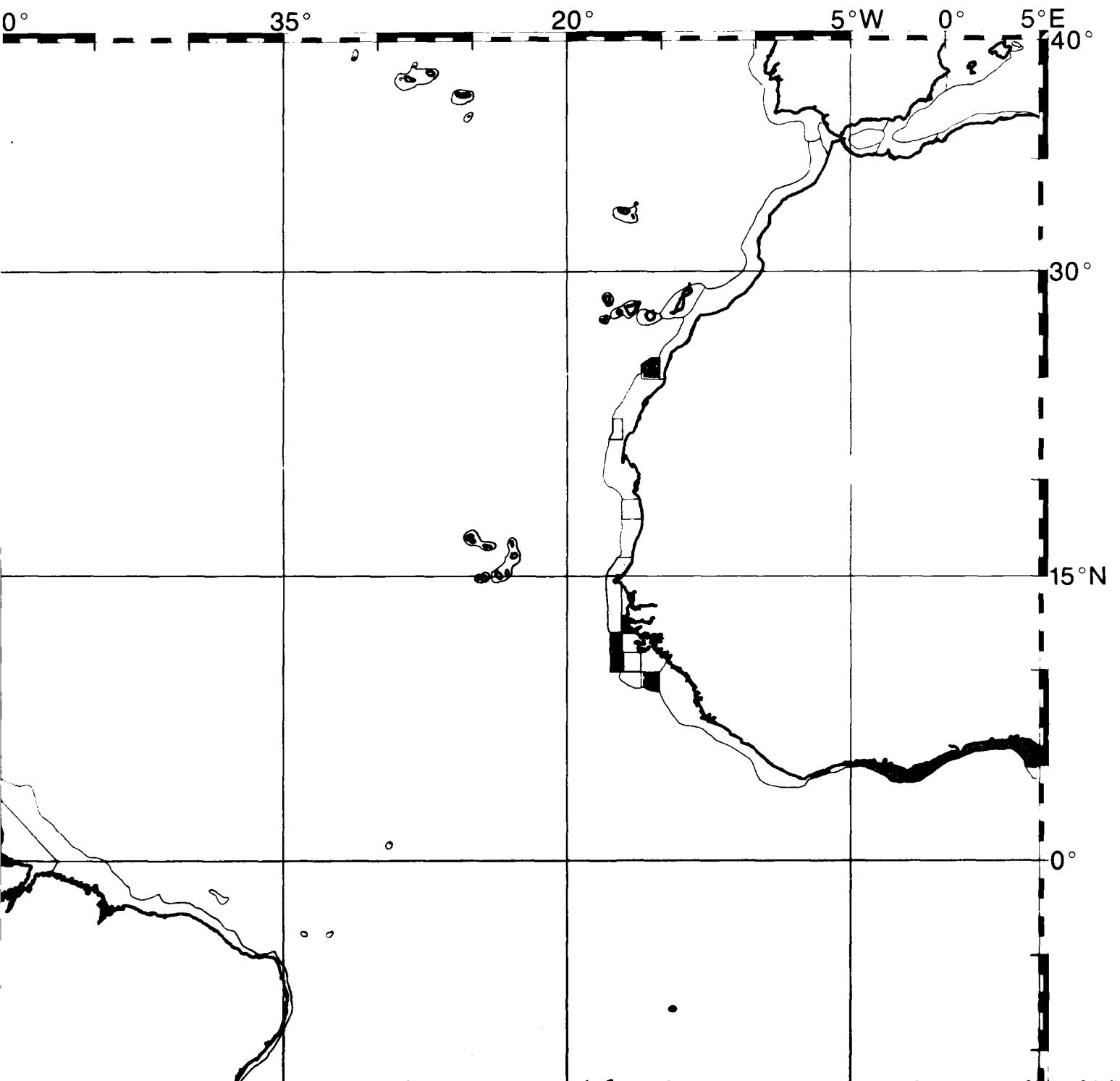
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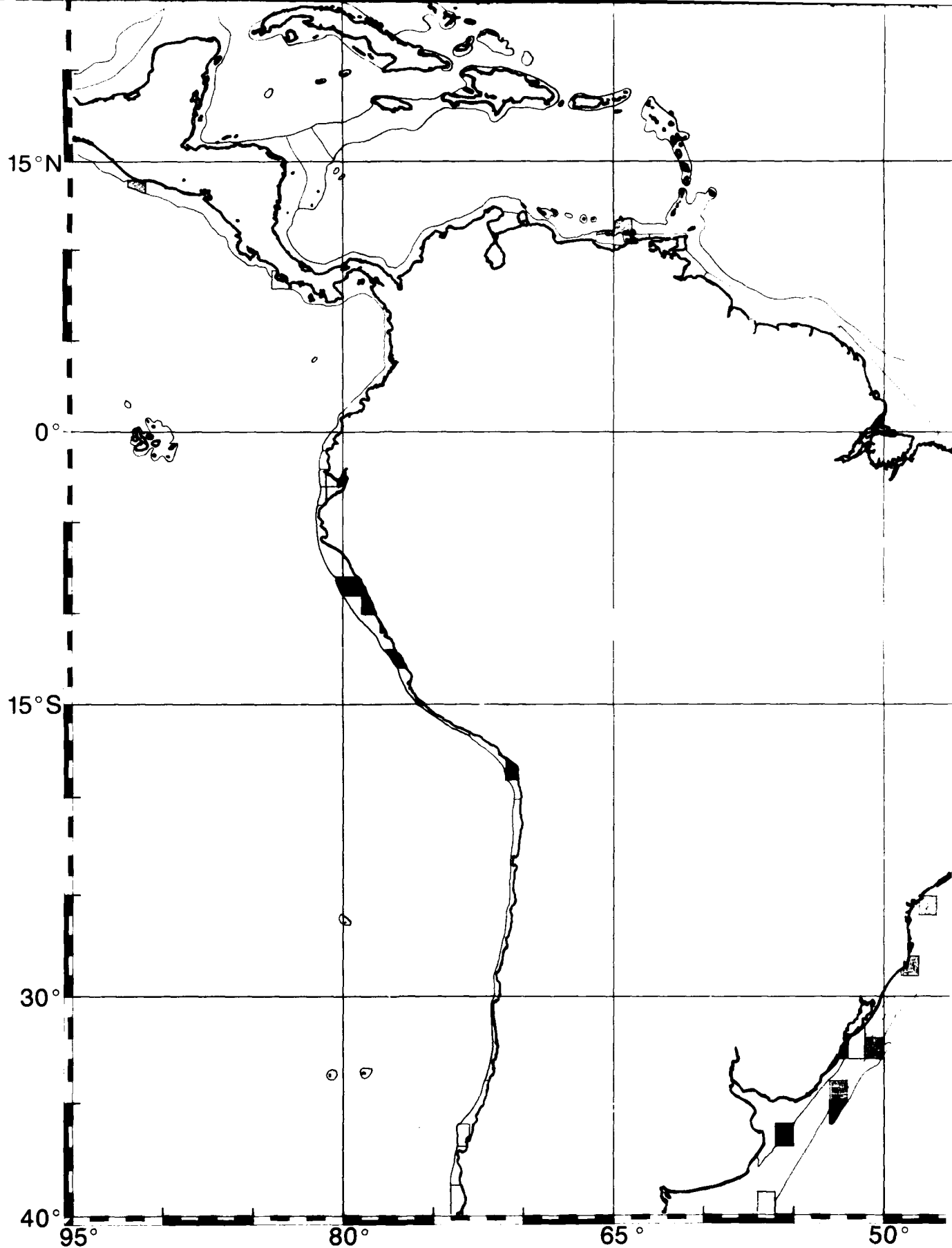
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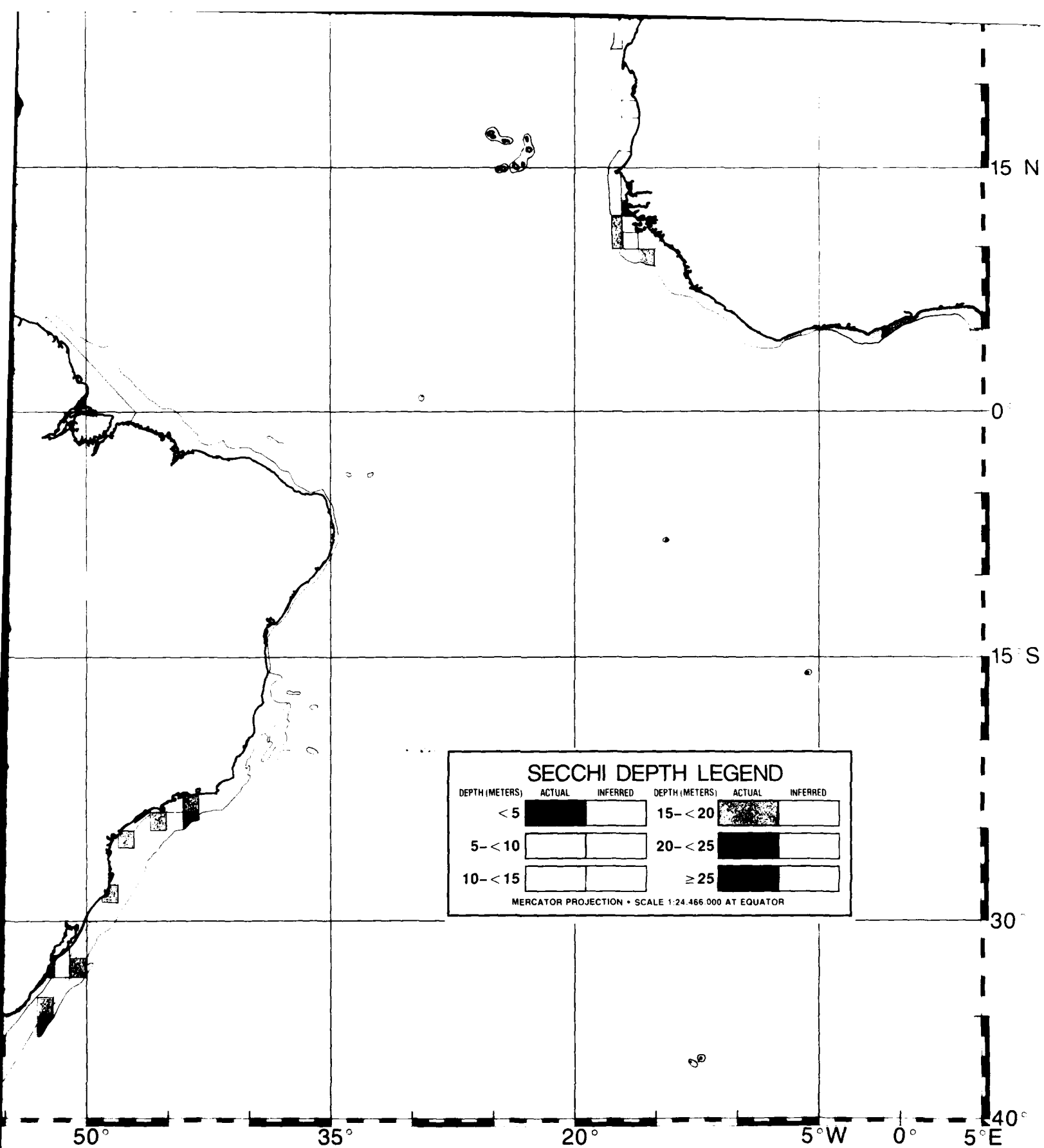


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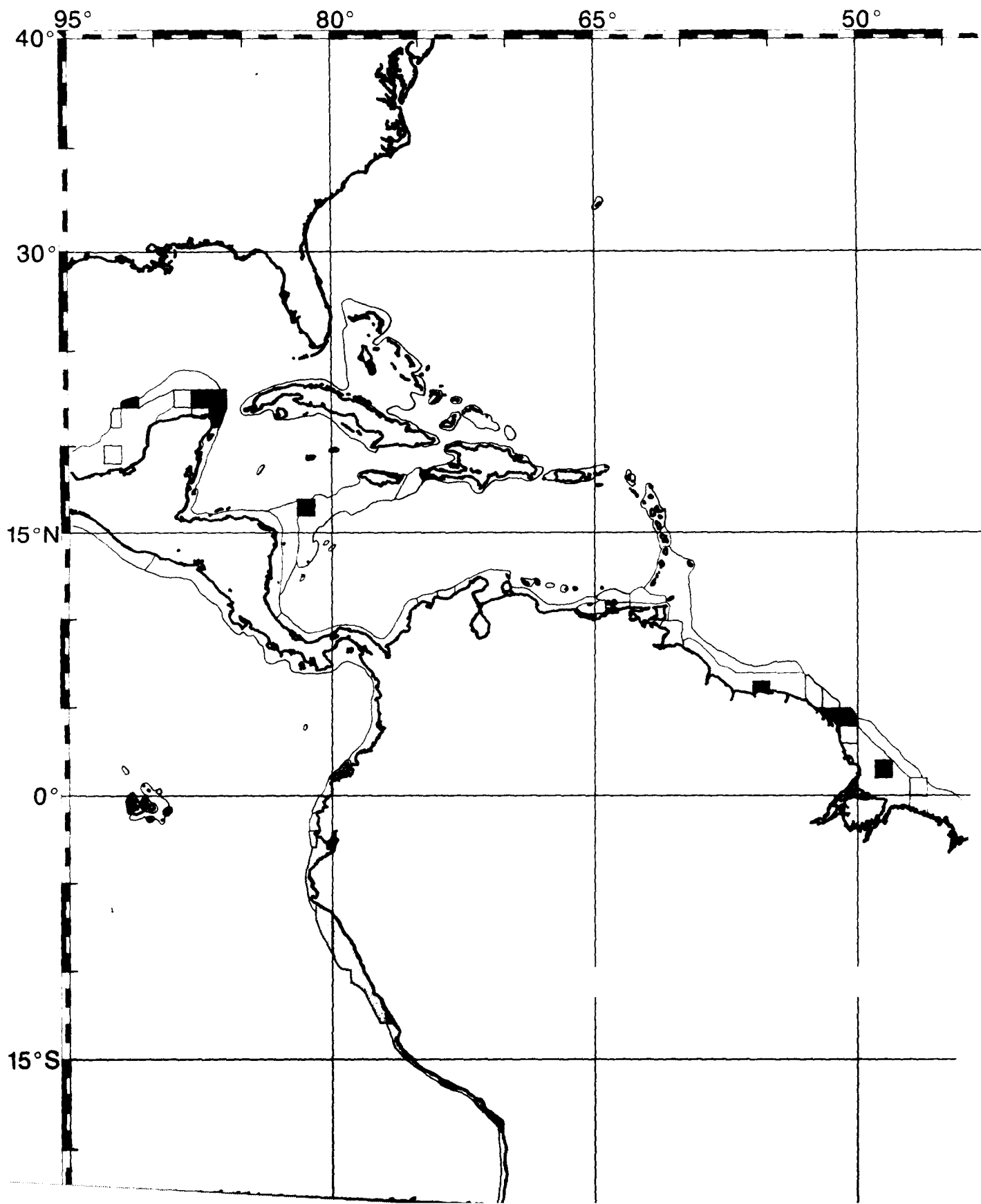
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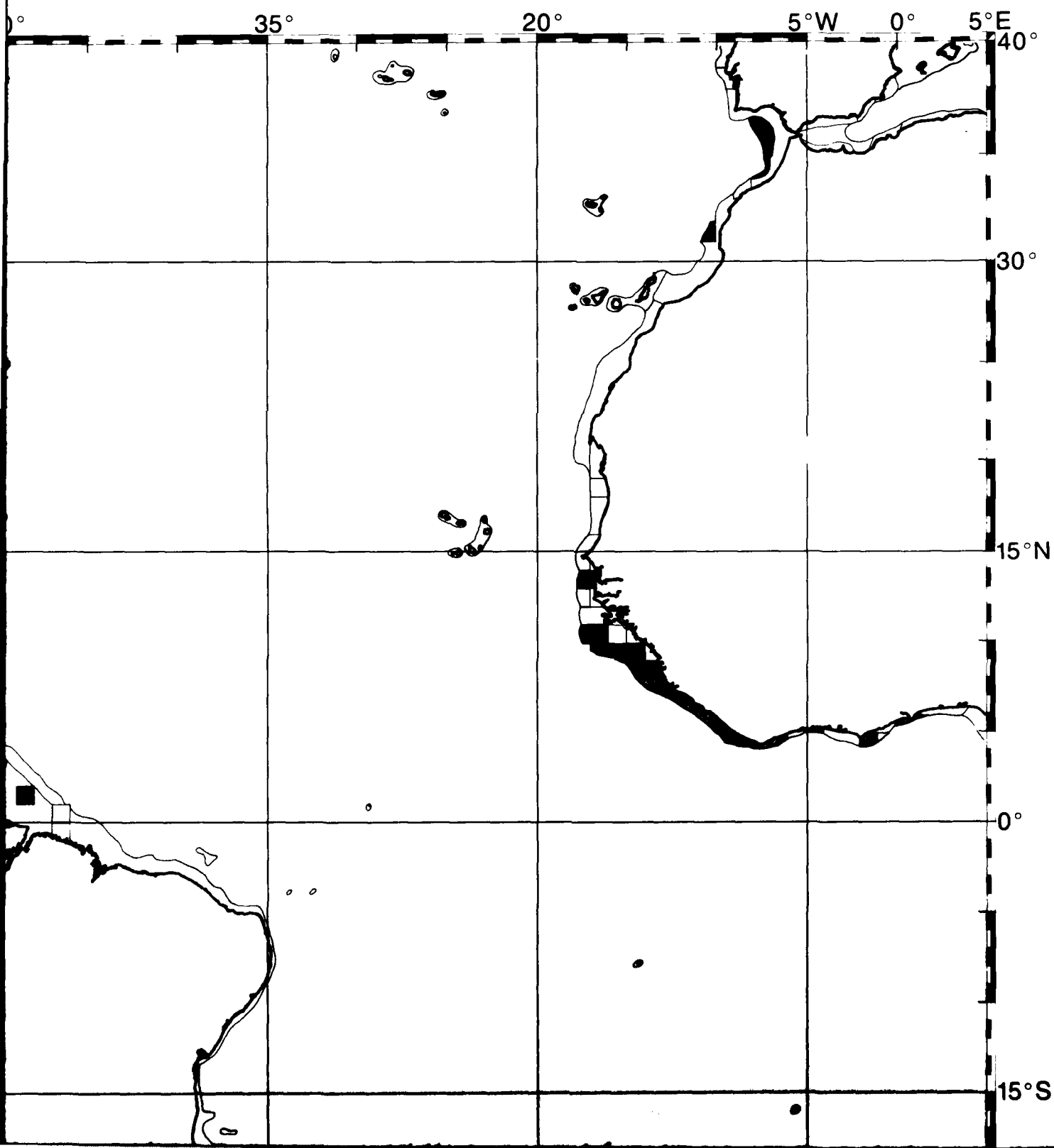
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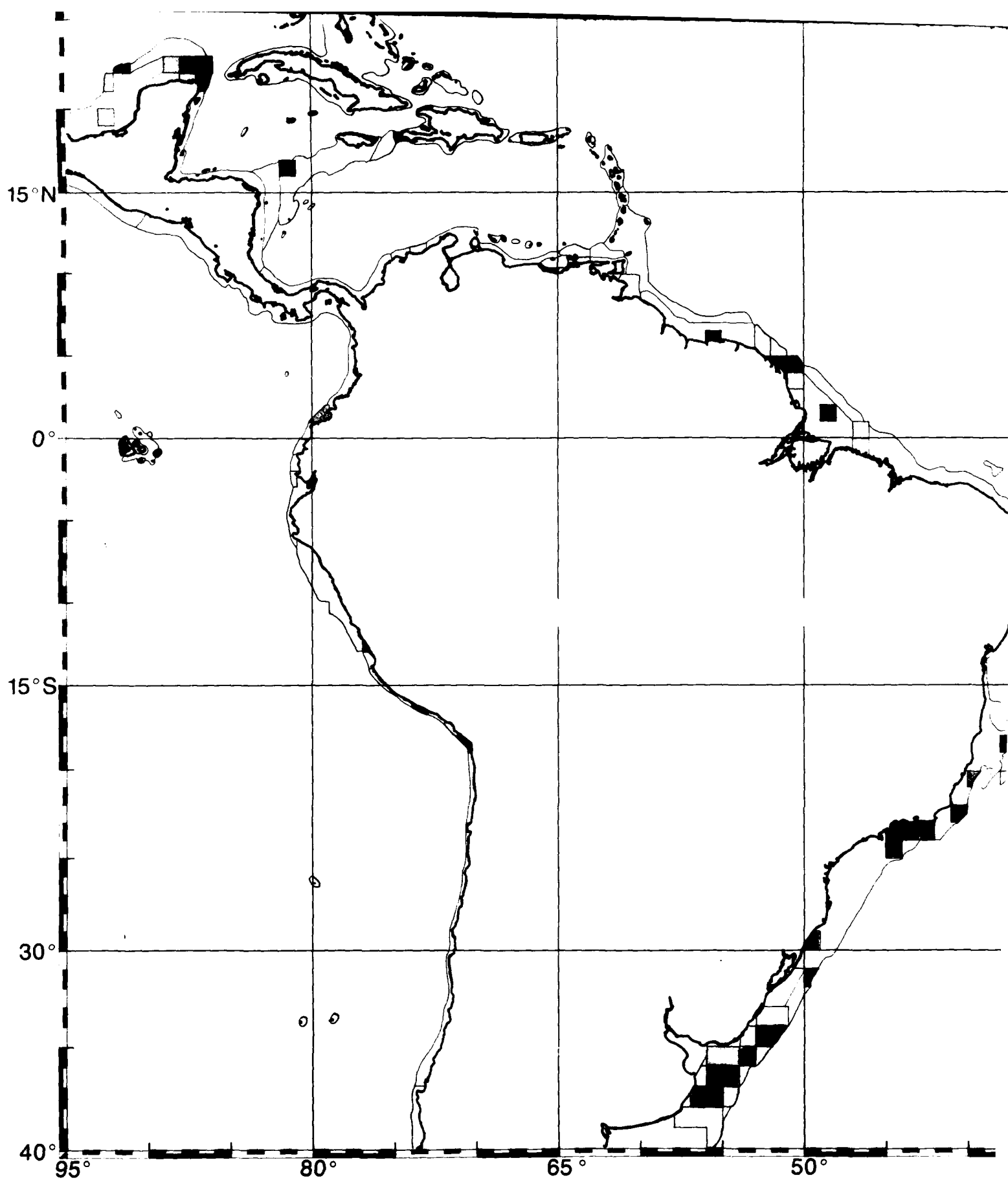
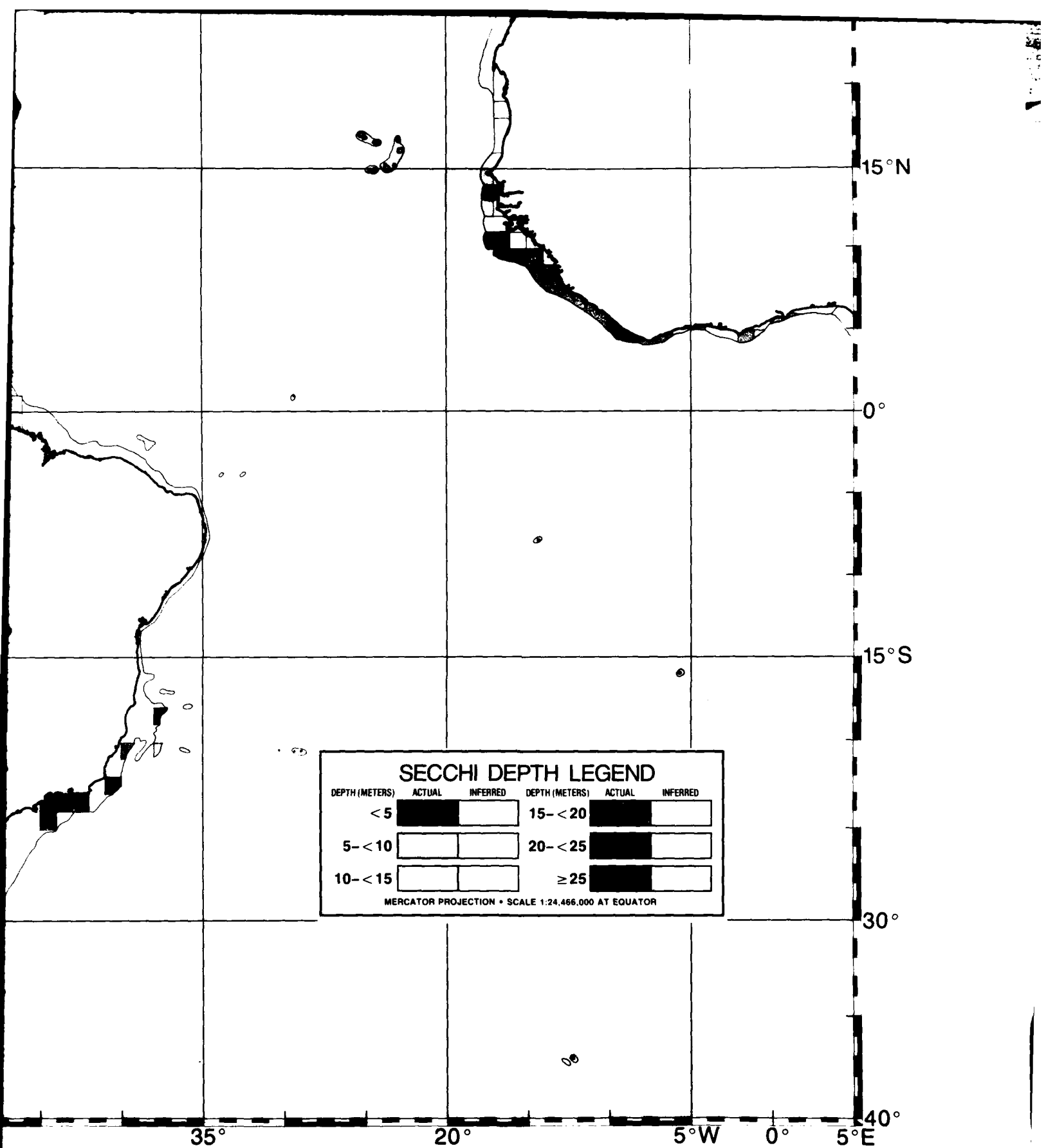
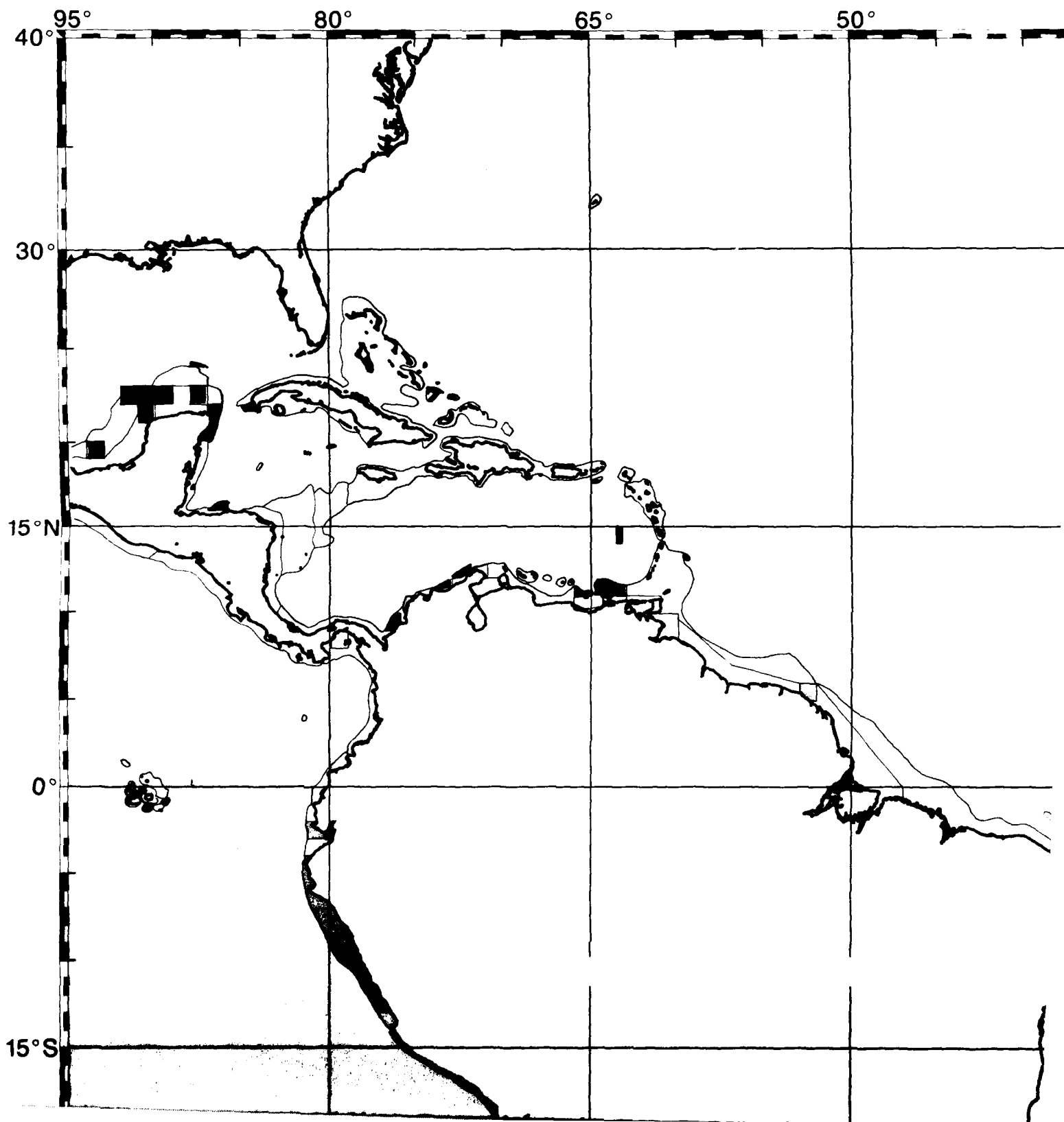


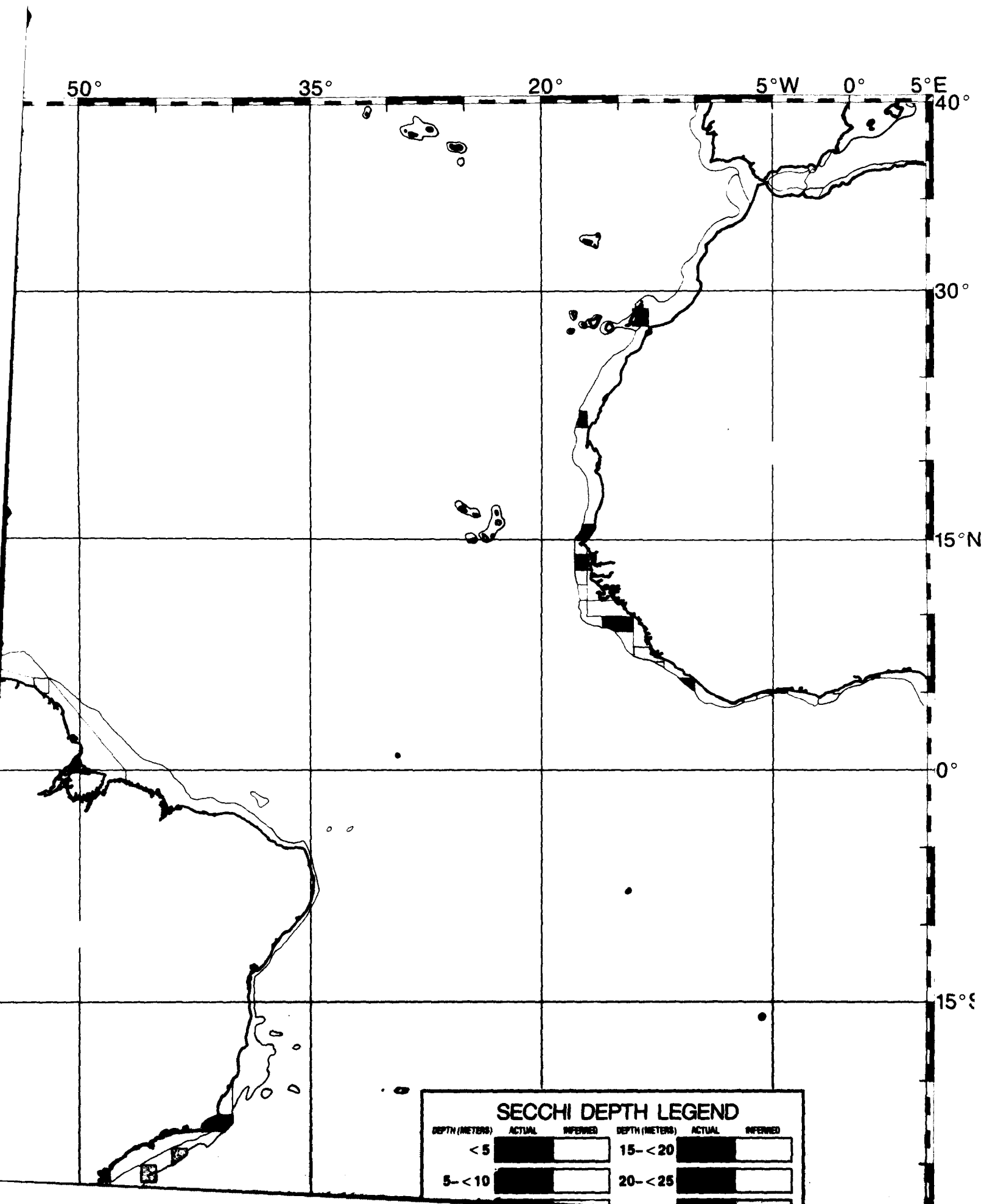
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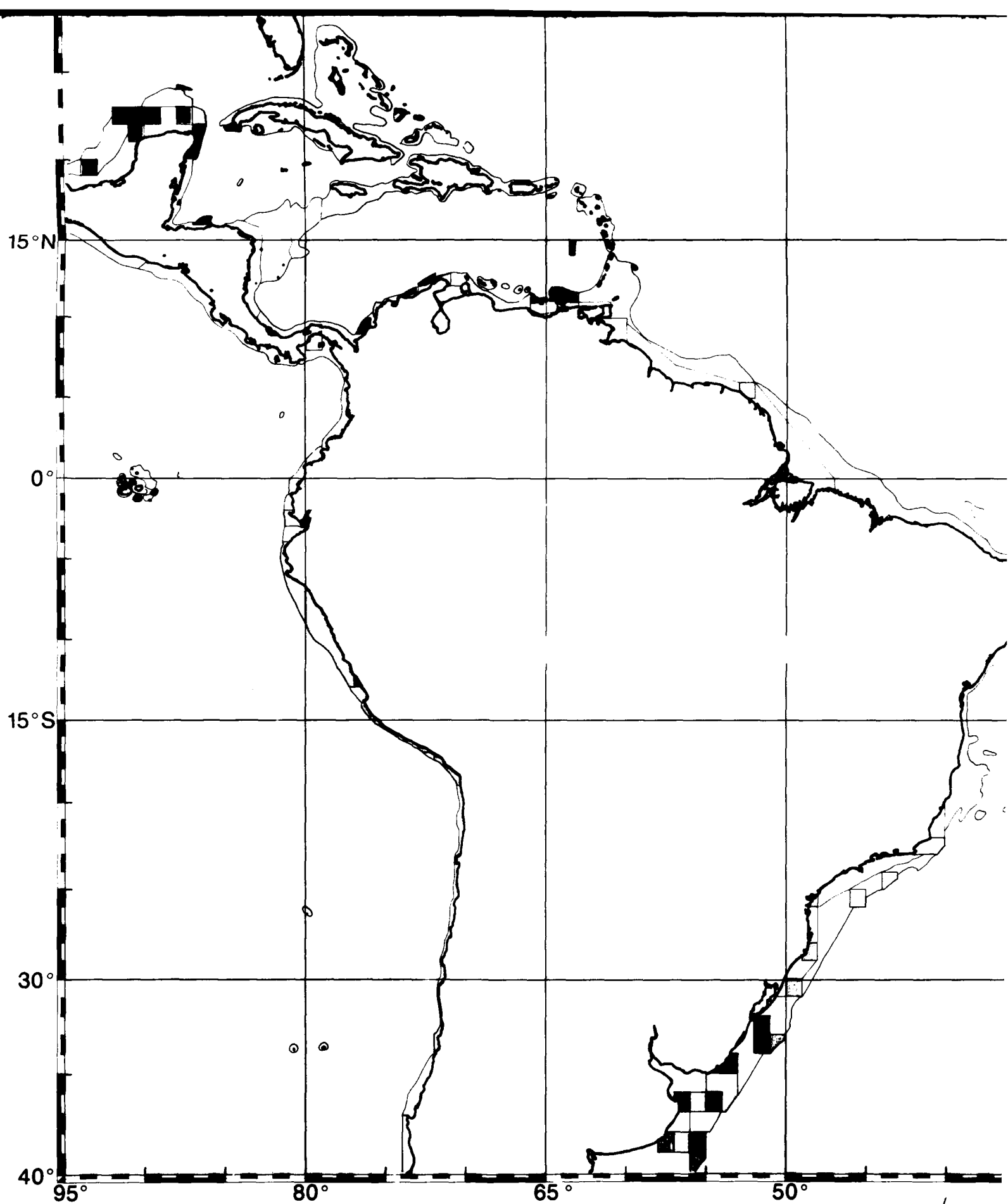
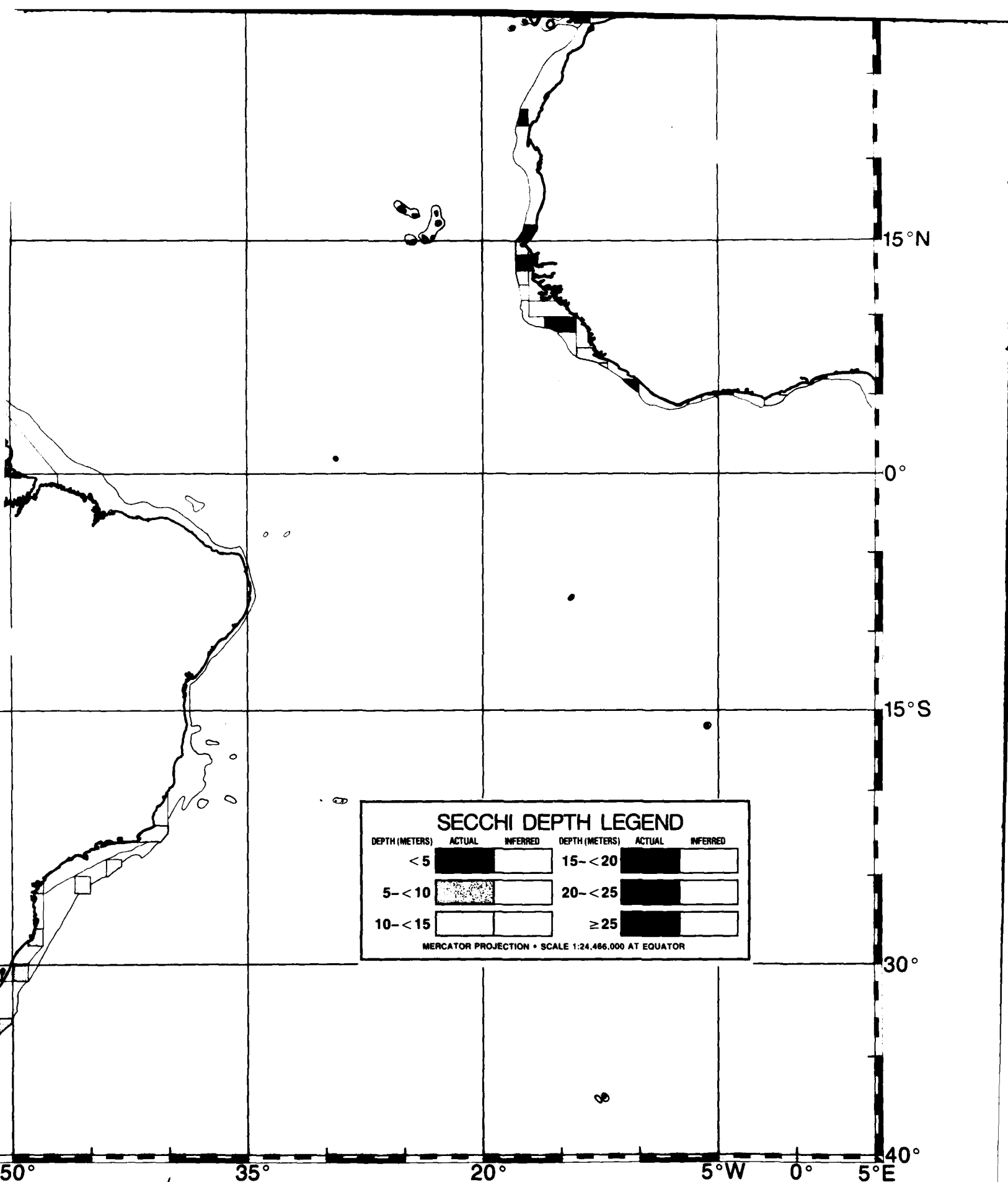
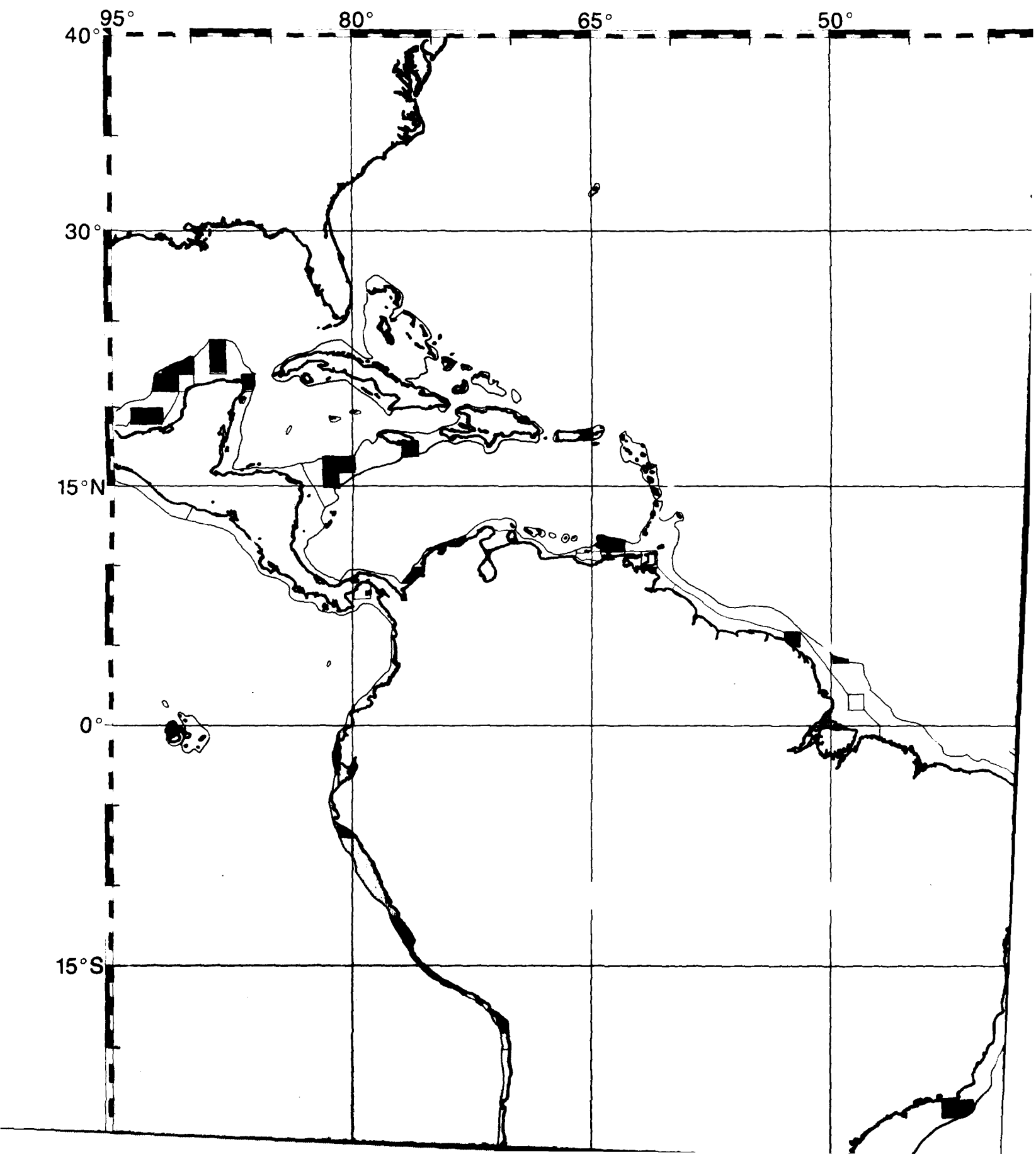


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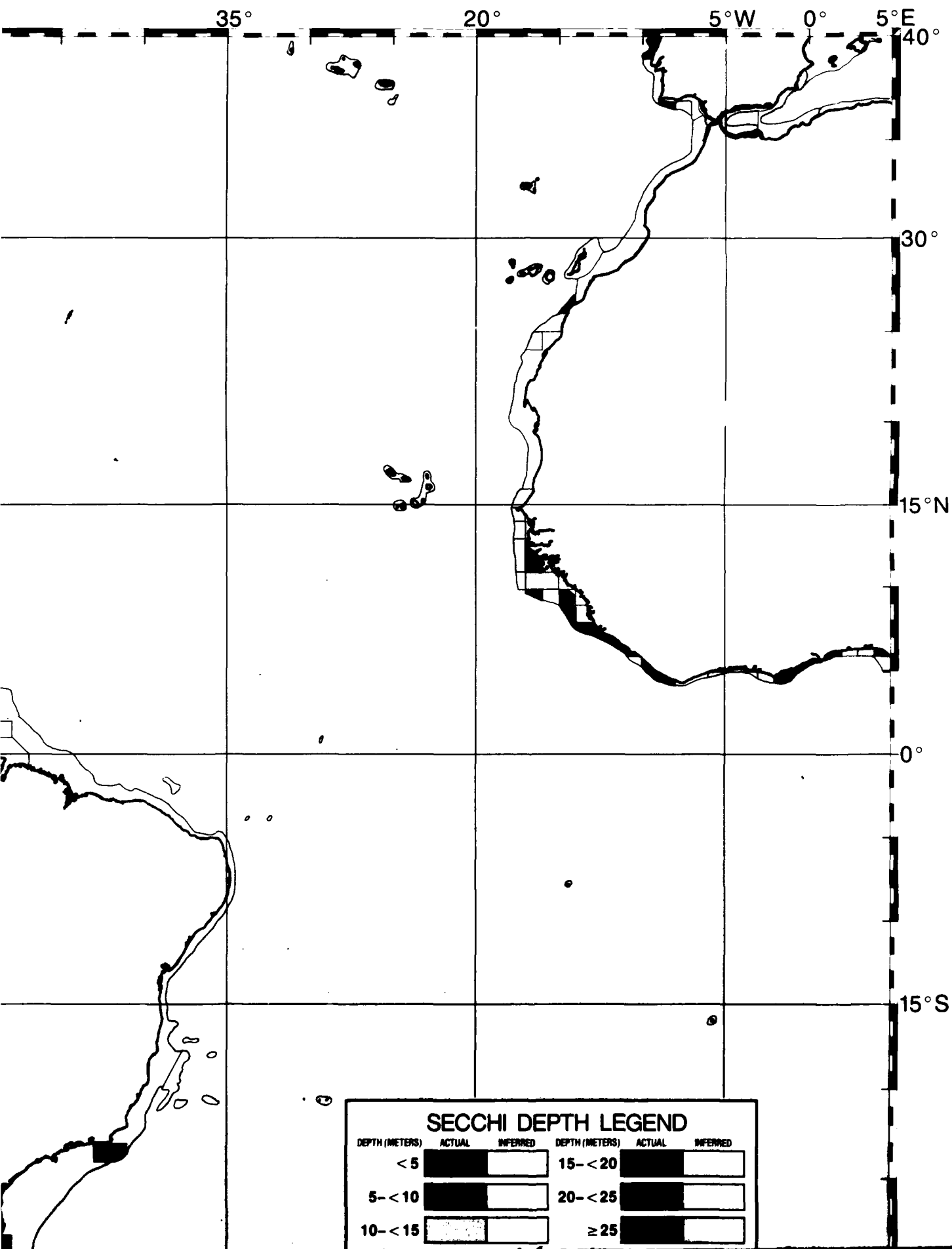


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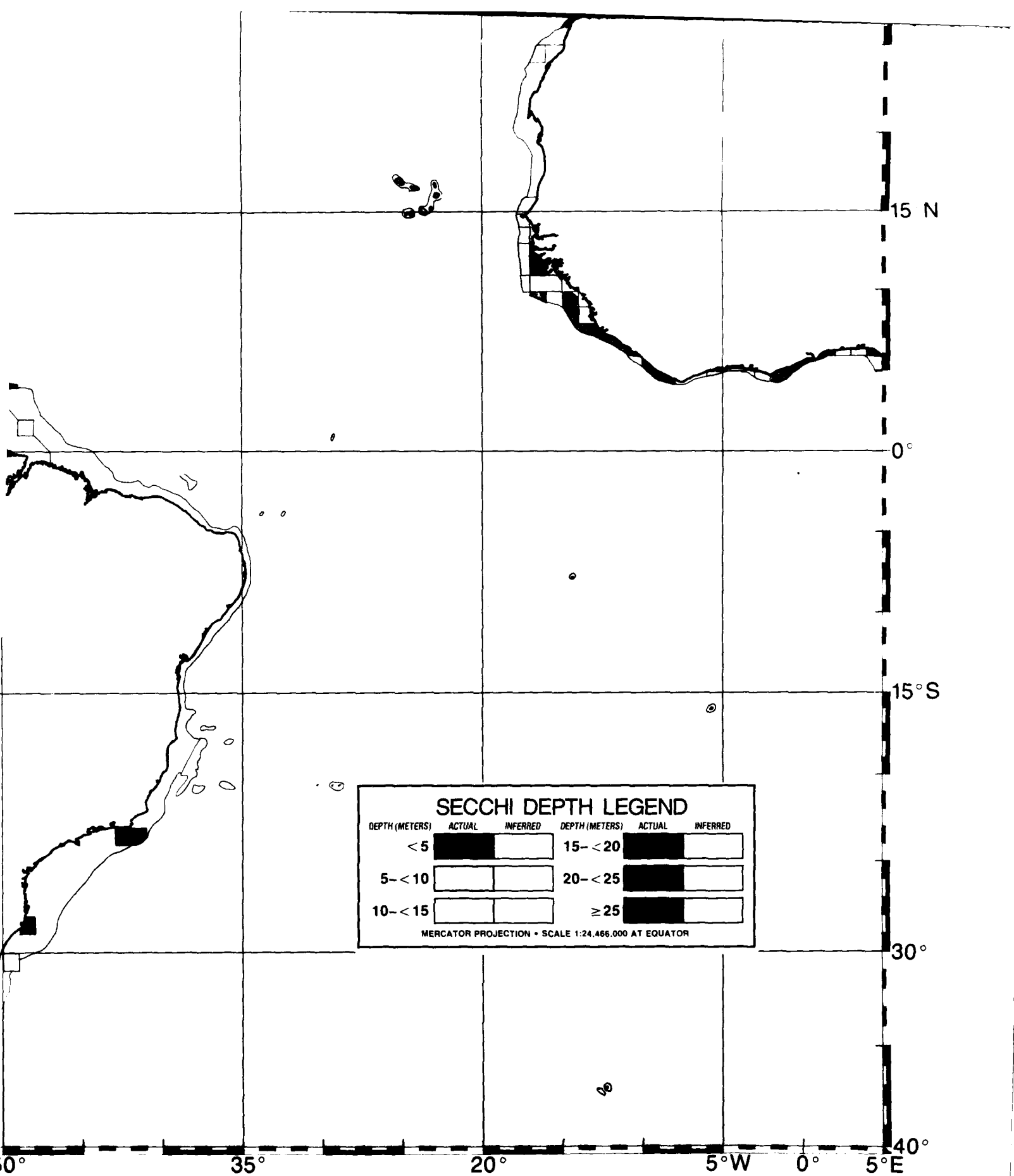






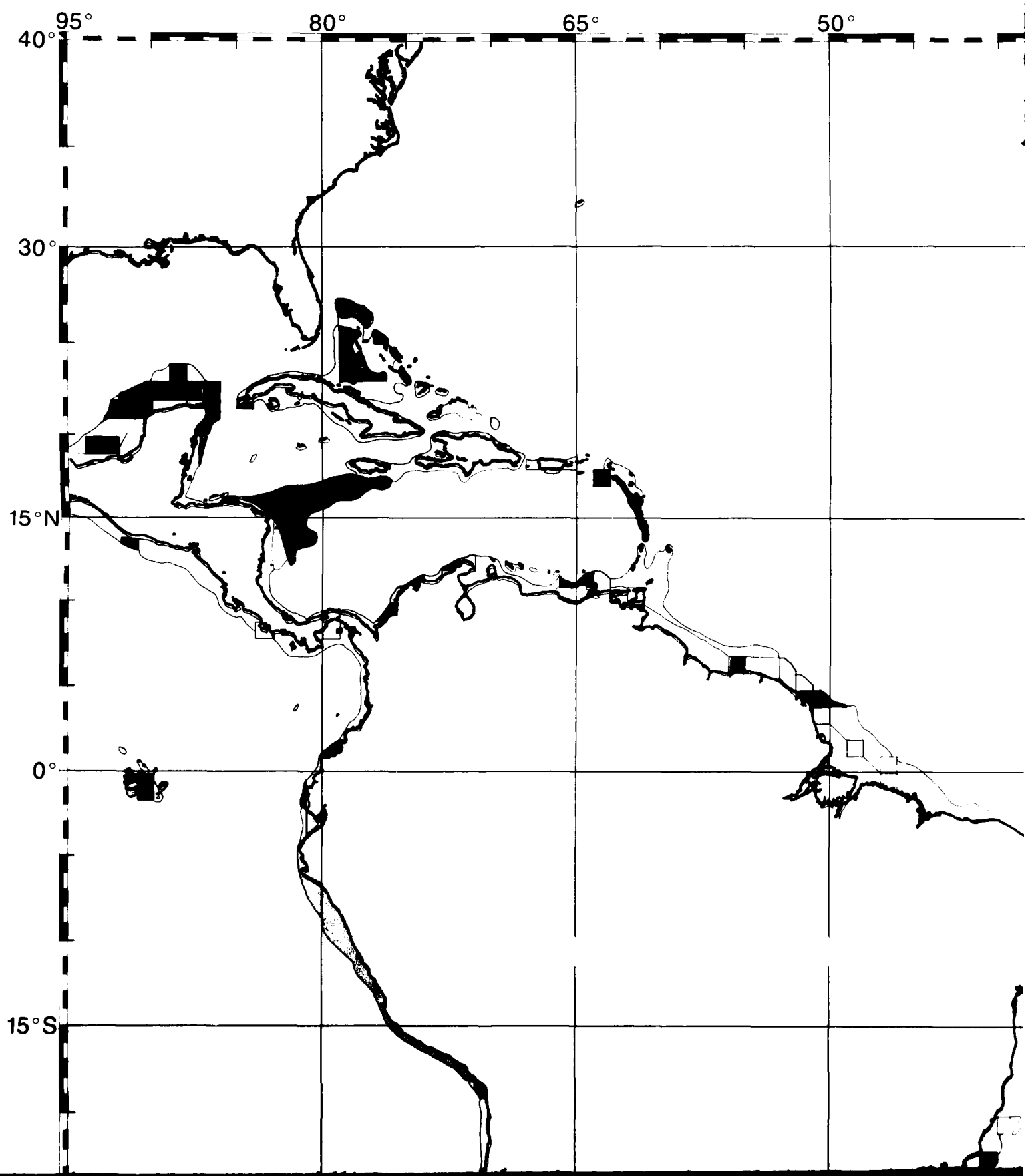


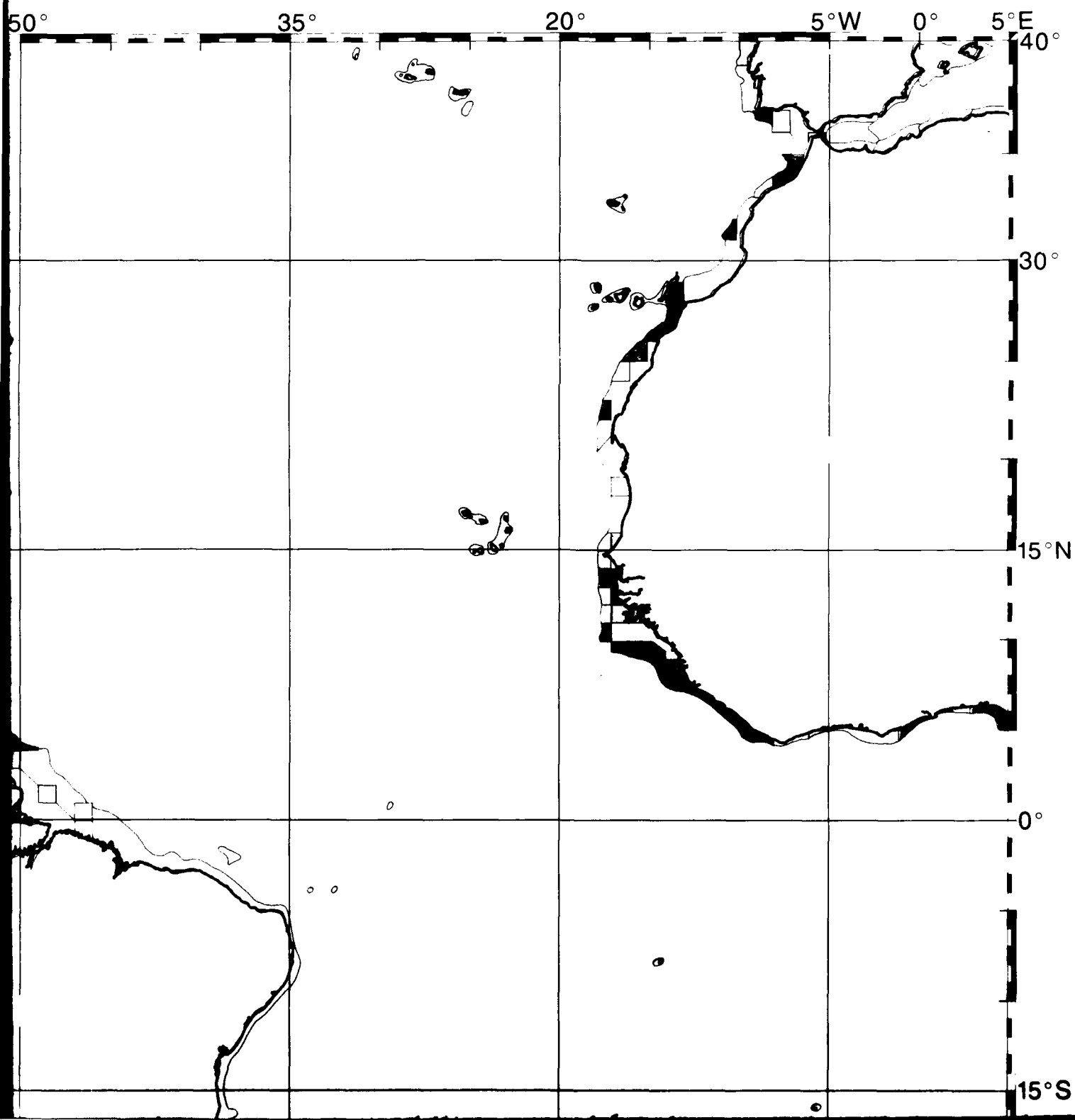




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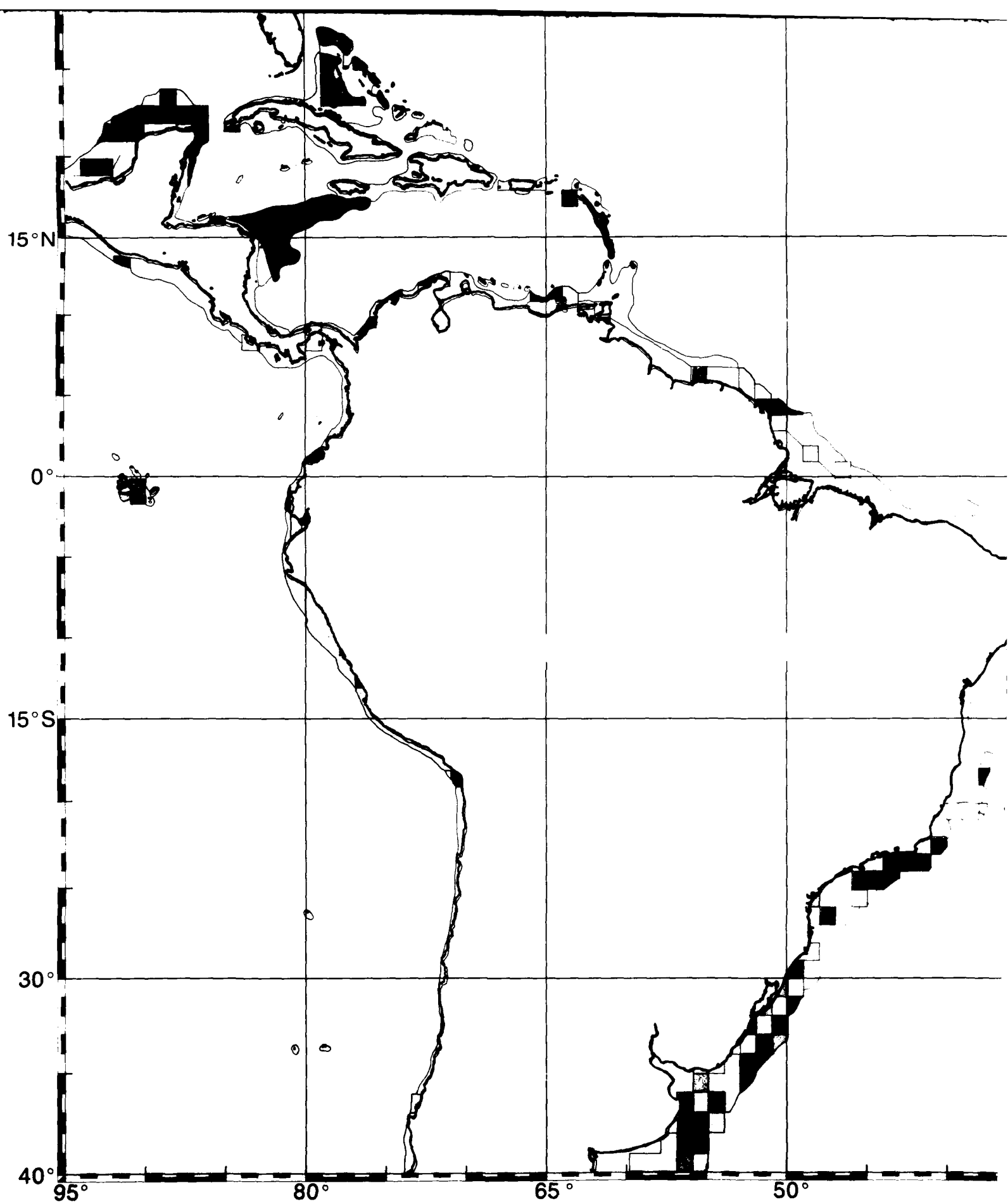
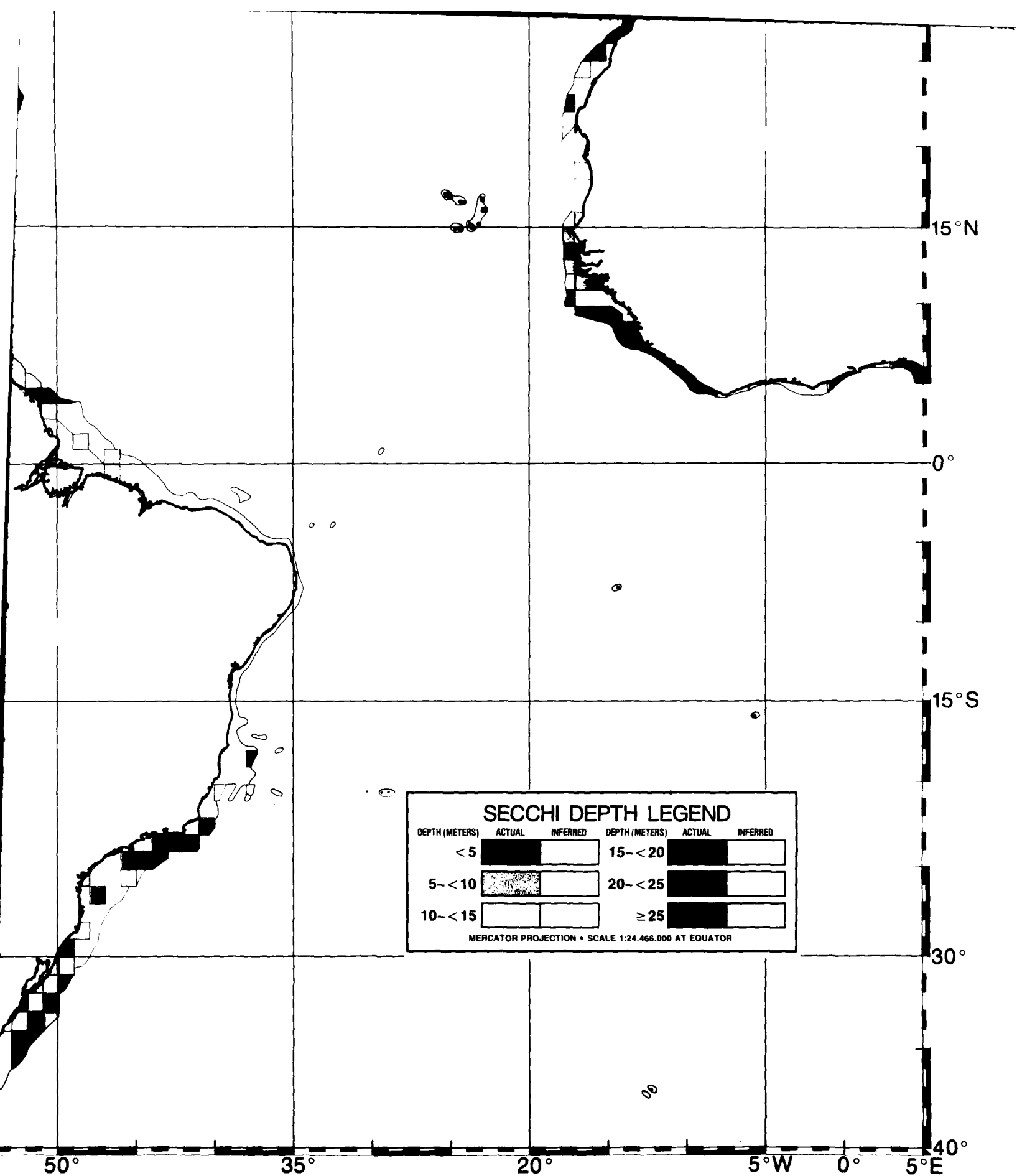
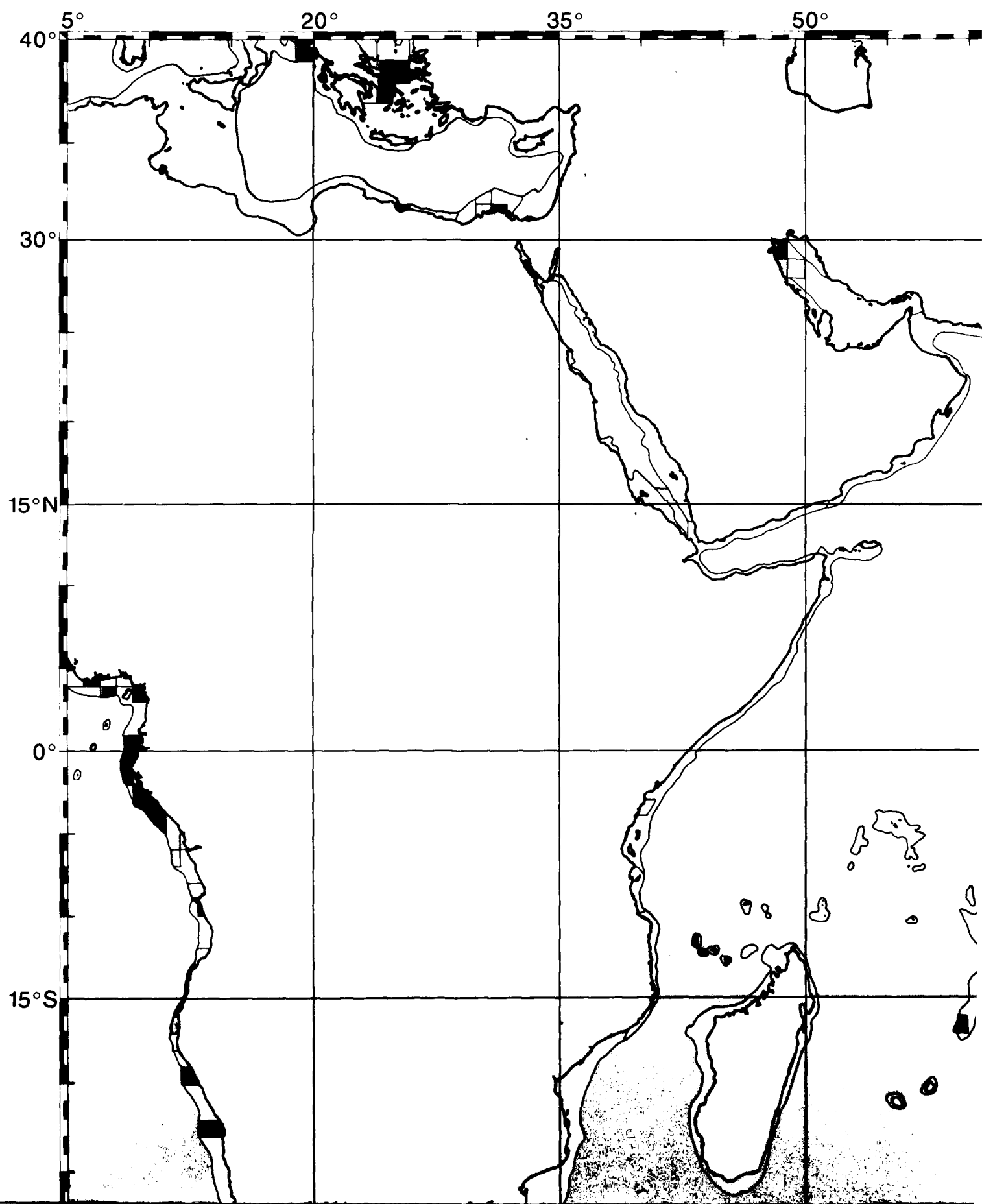


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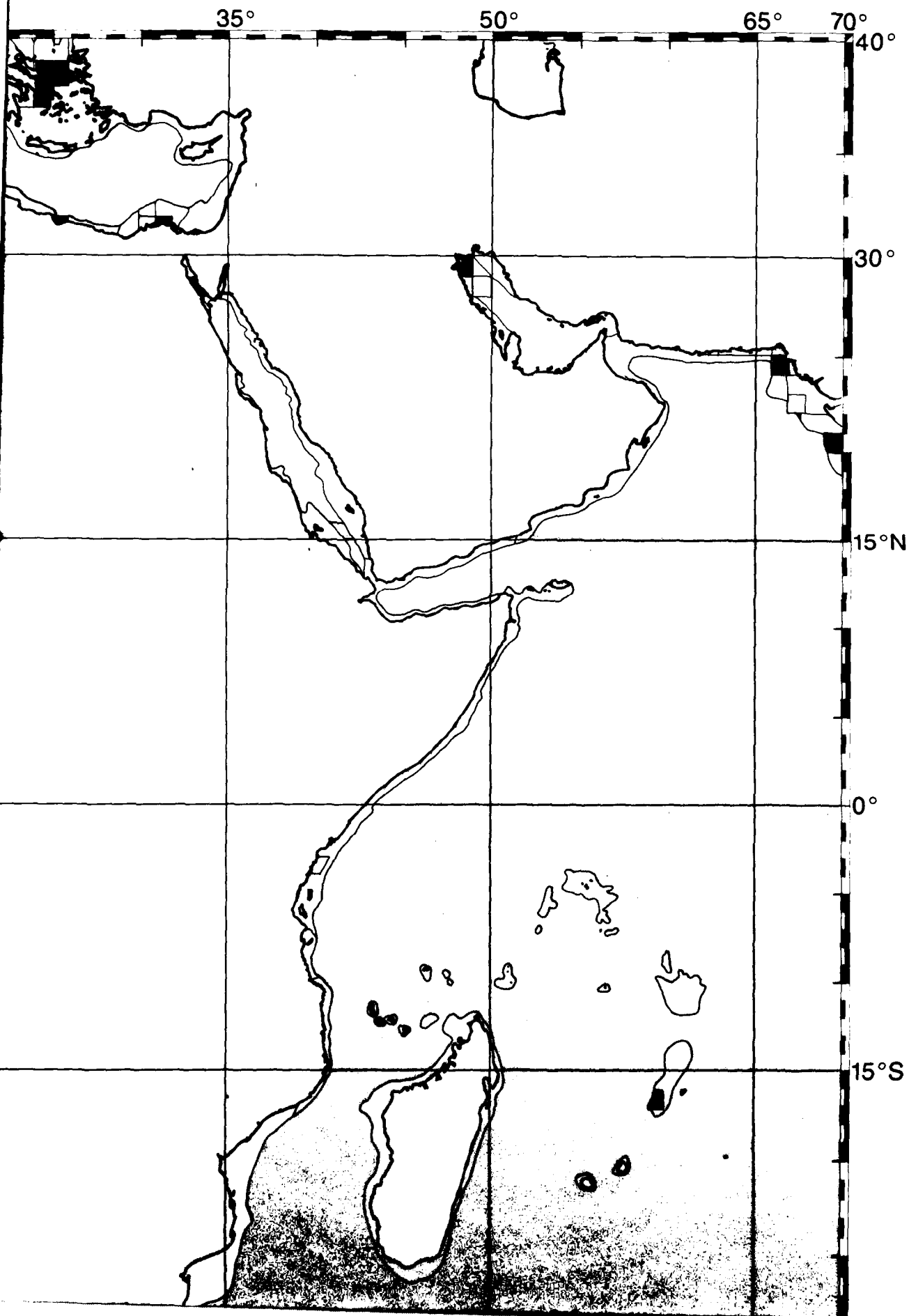


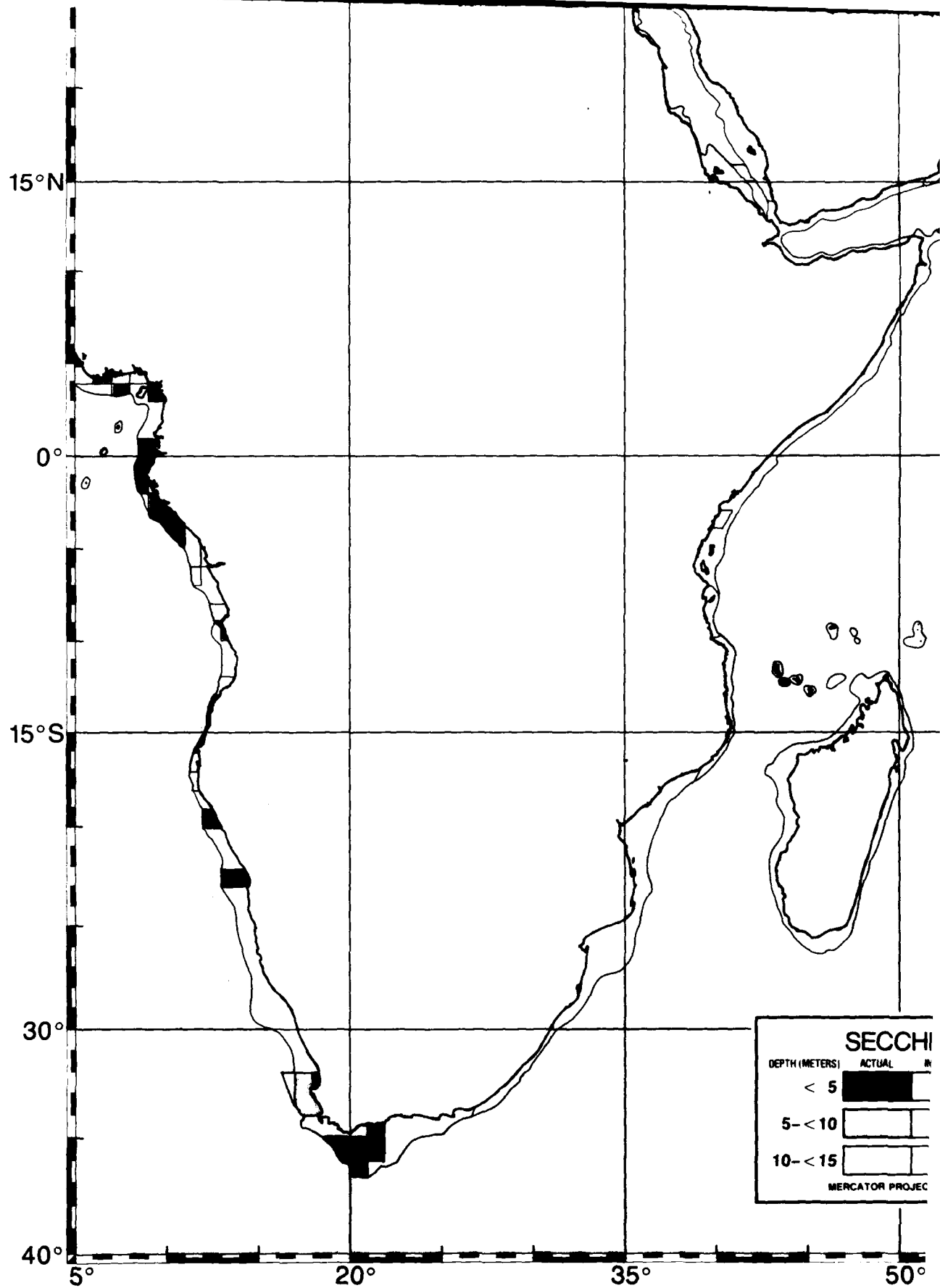
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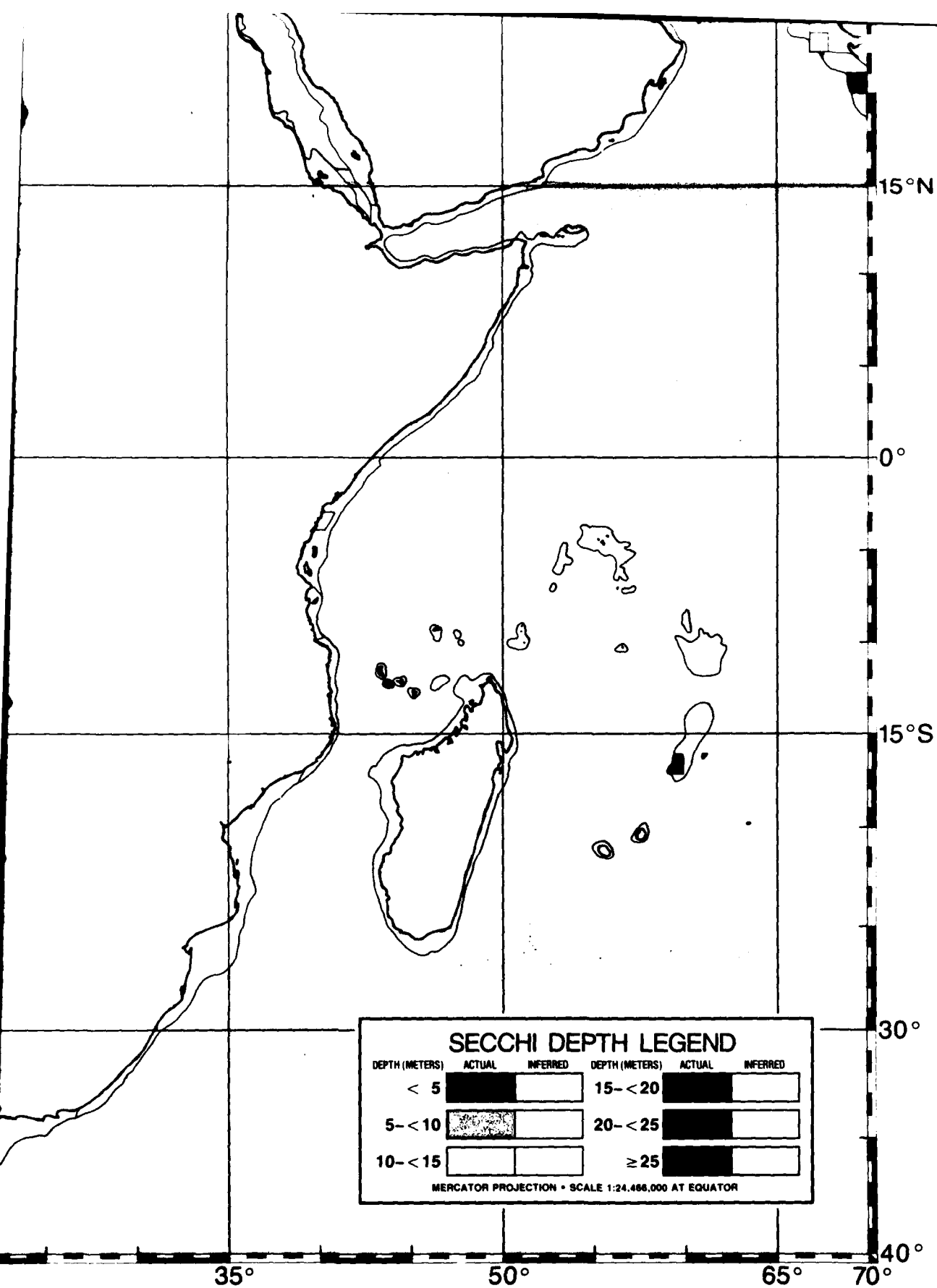






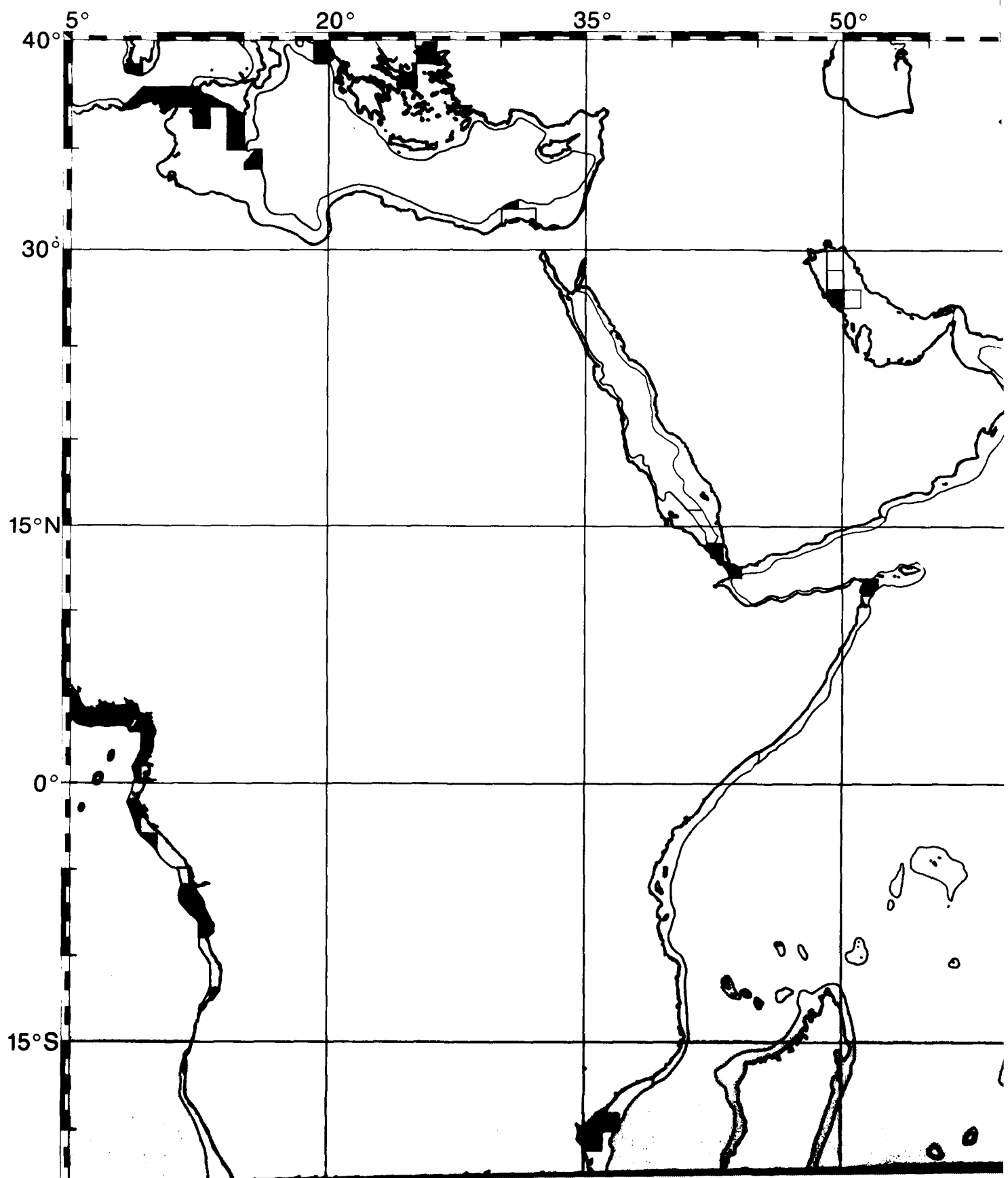


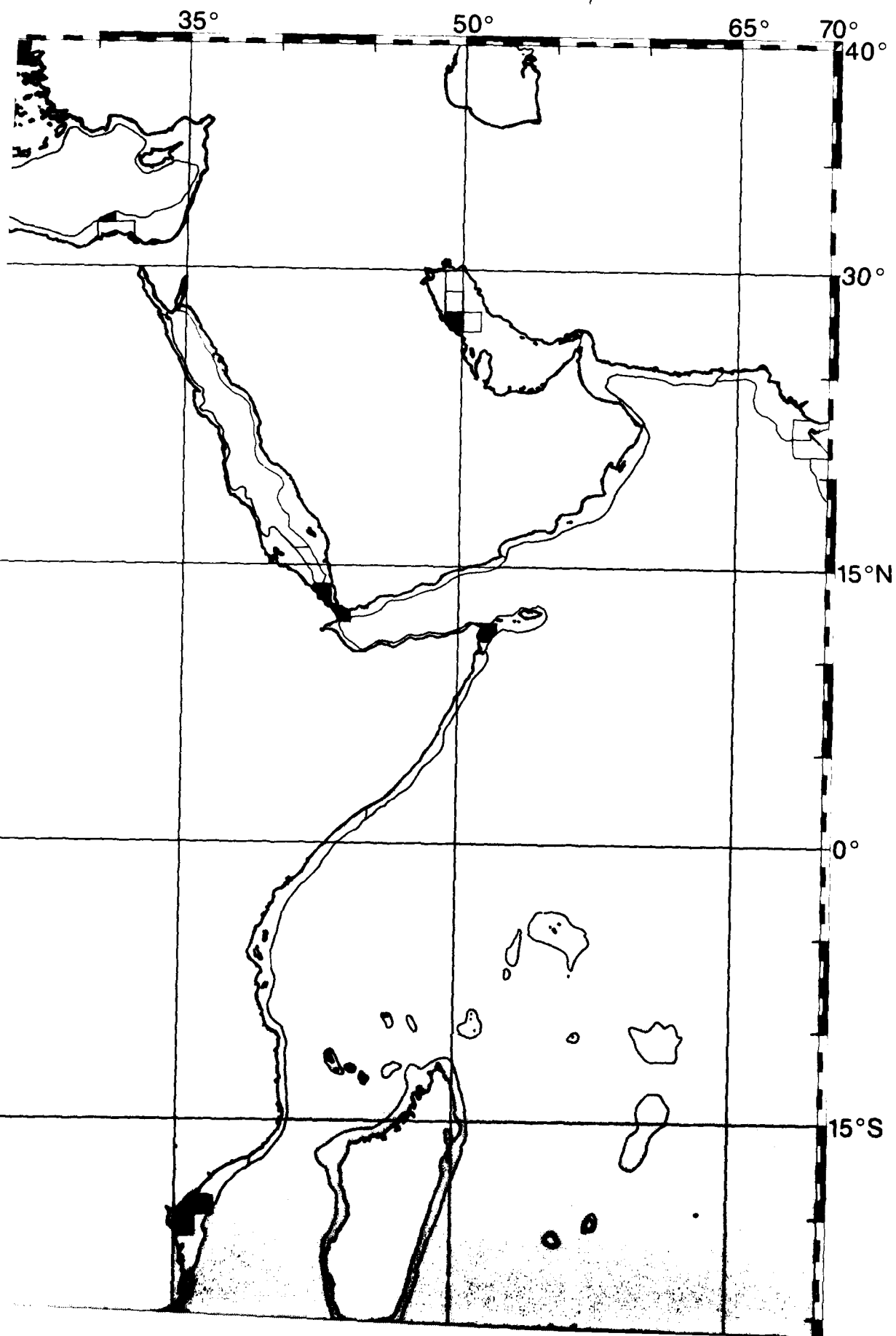




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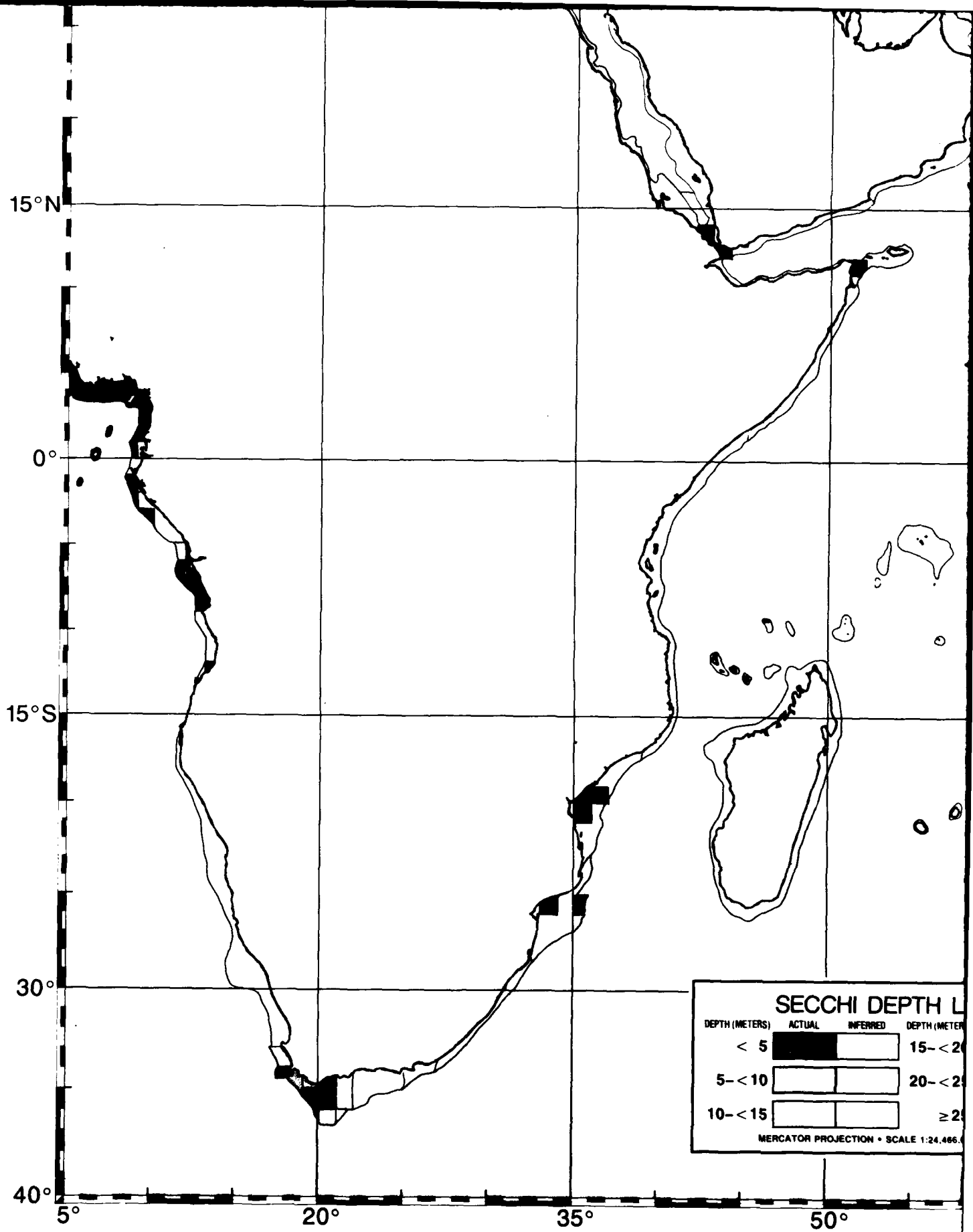
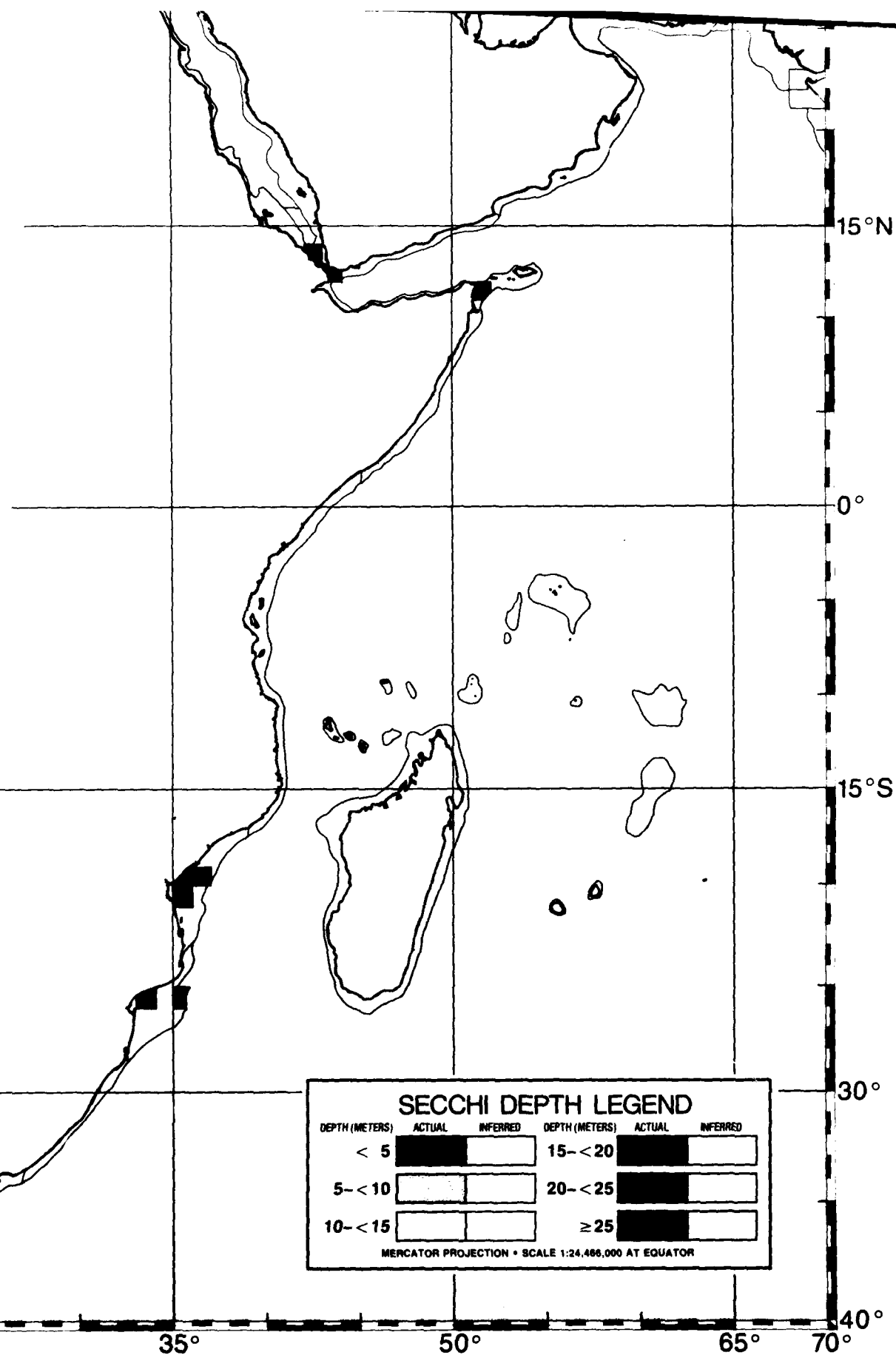


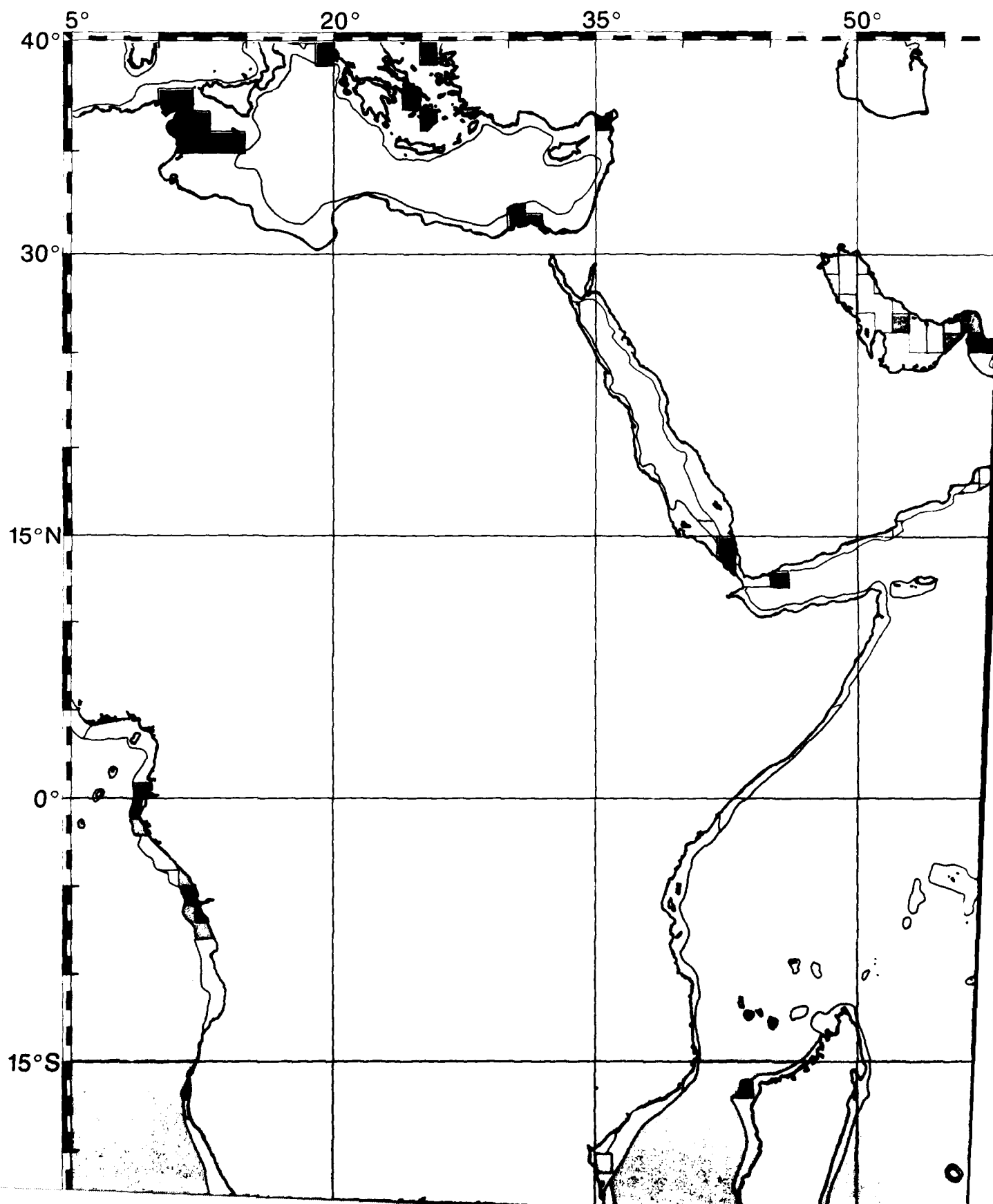
PLATE VII APRIL-JUNE

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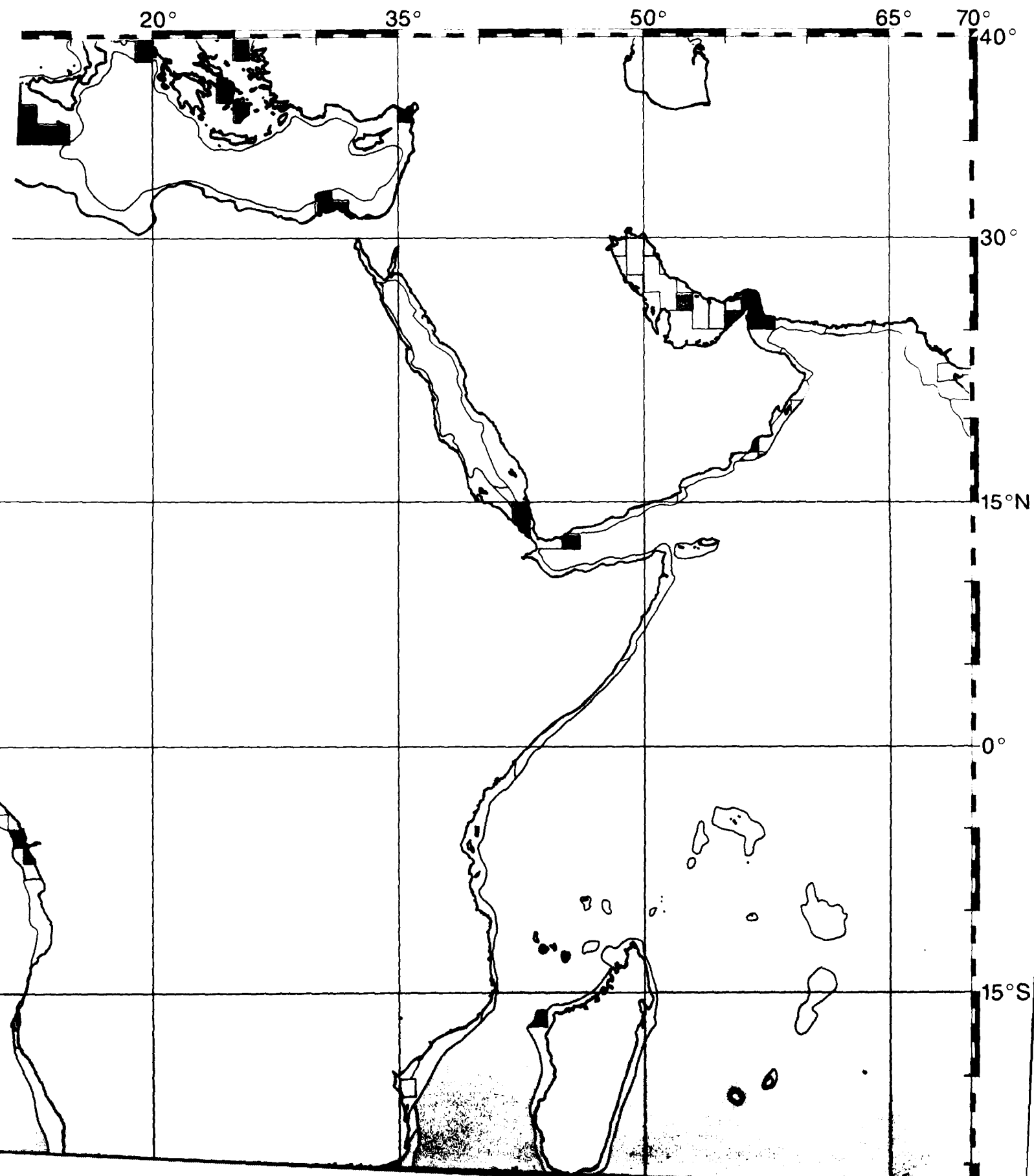


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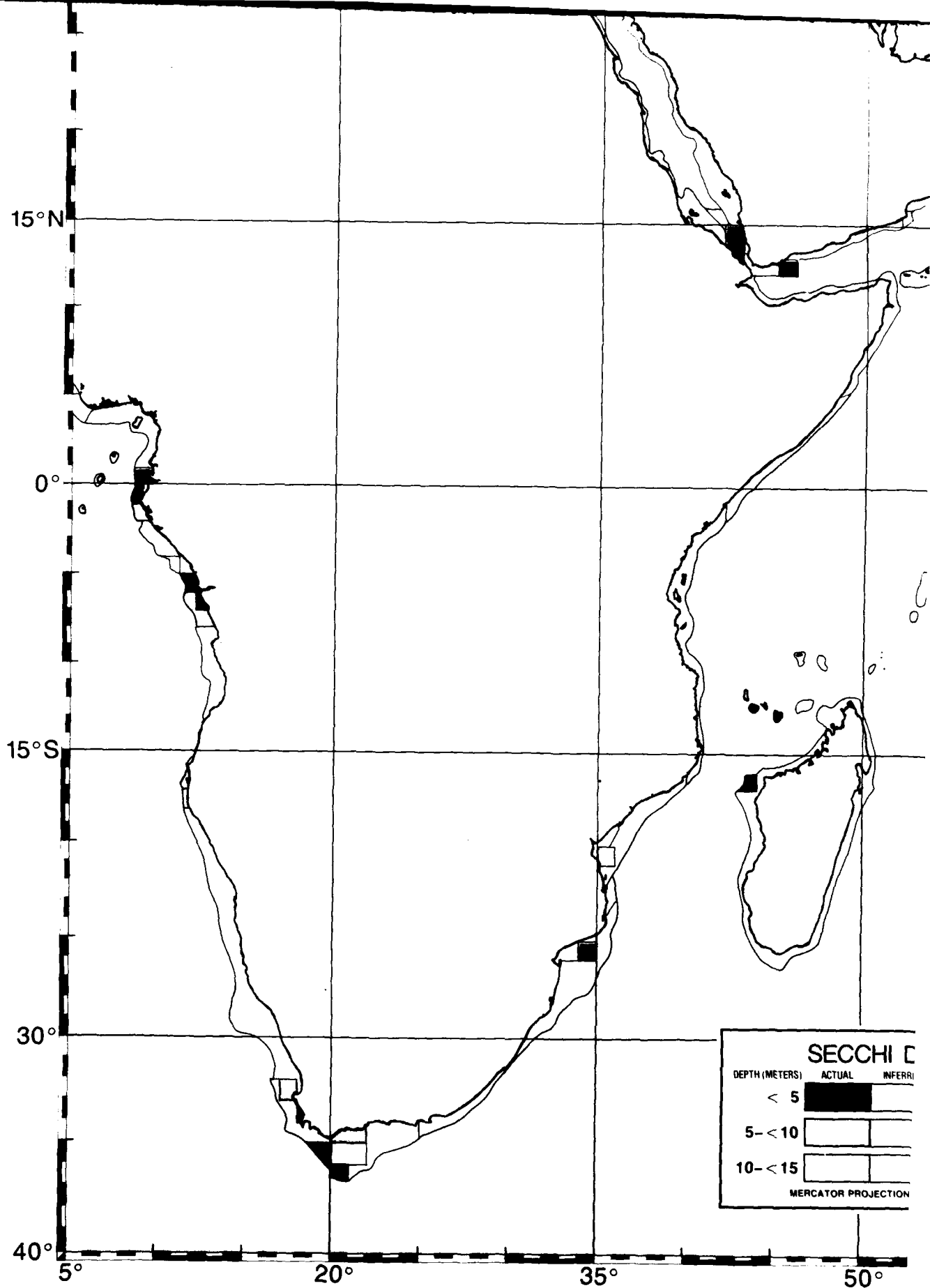
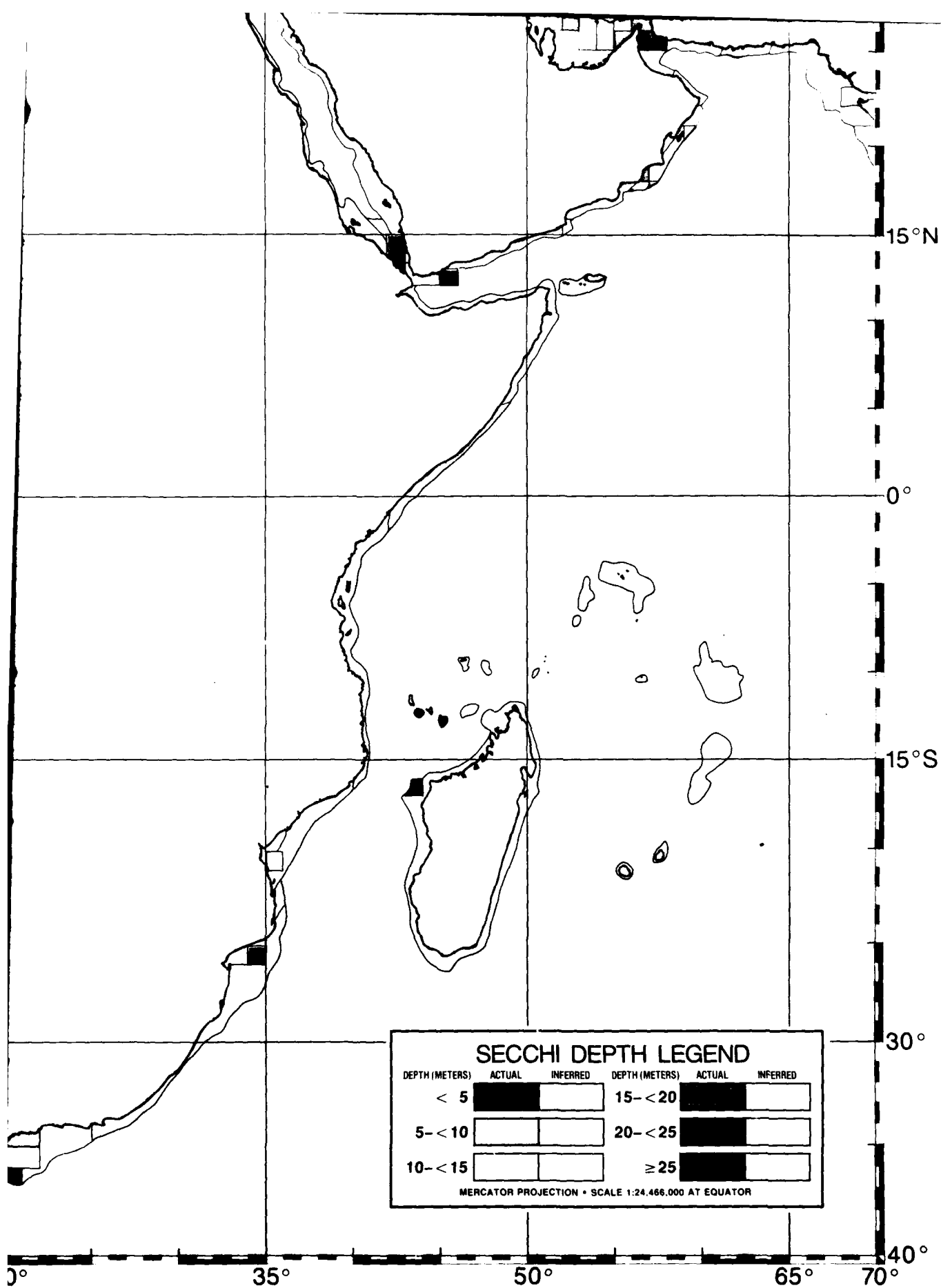


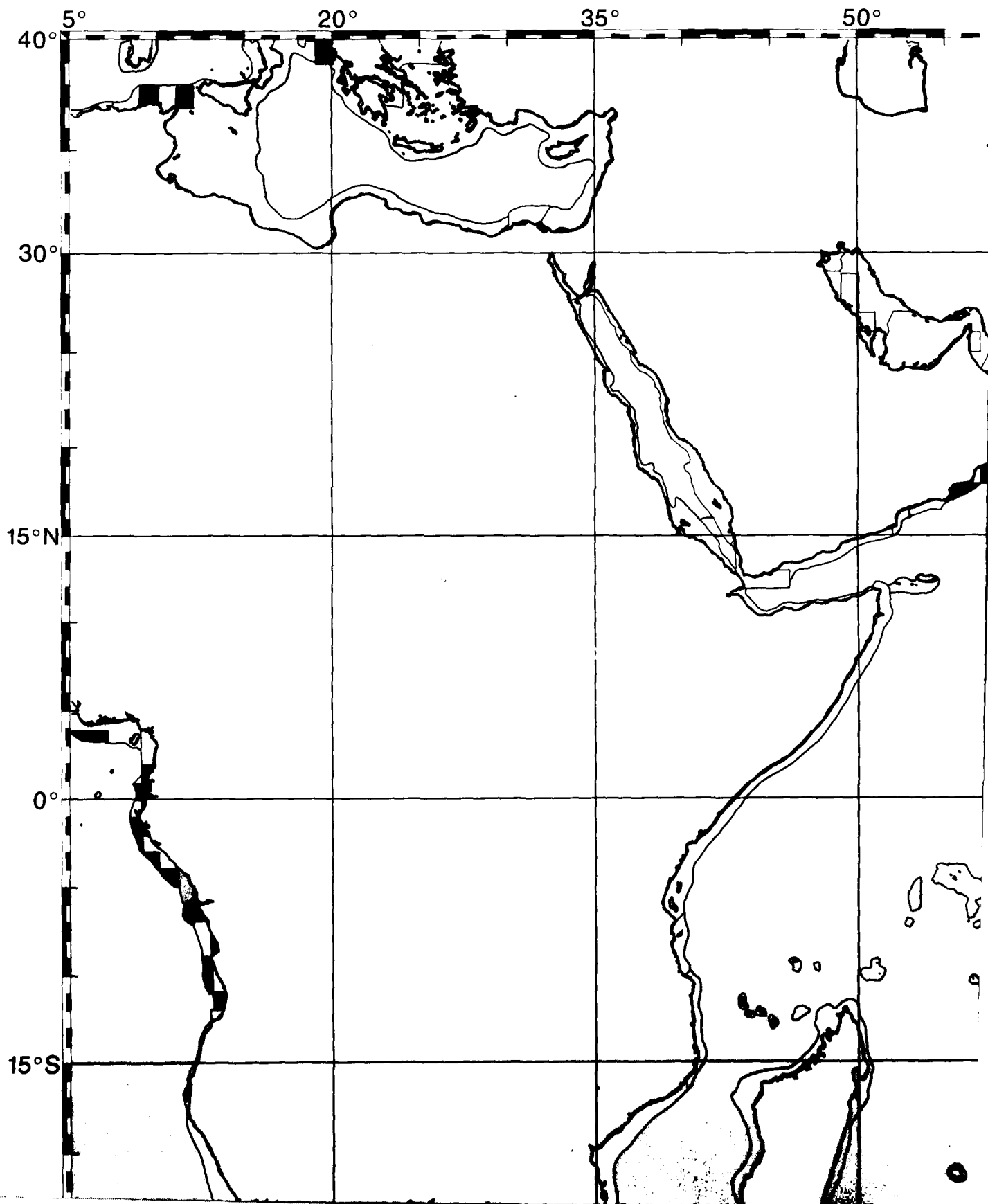
PLATE VIII JULY-SEPTEMBER

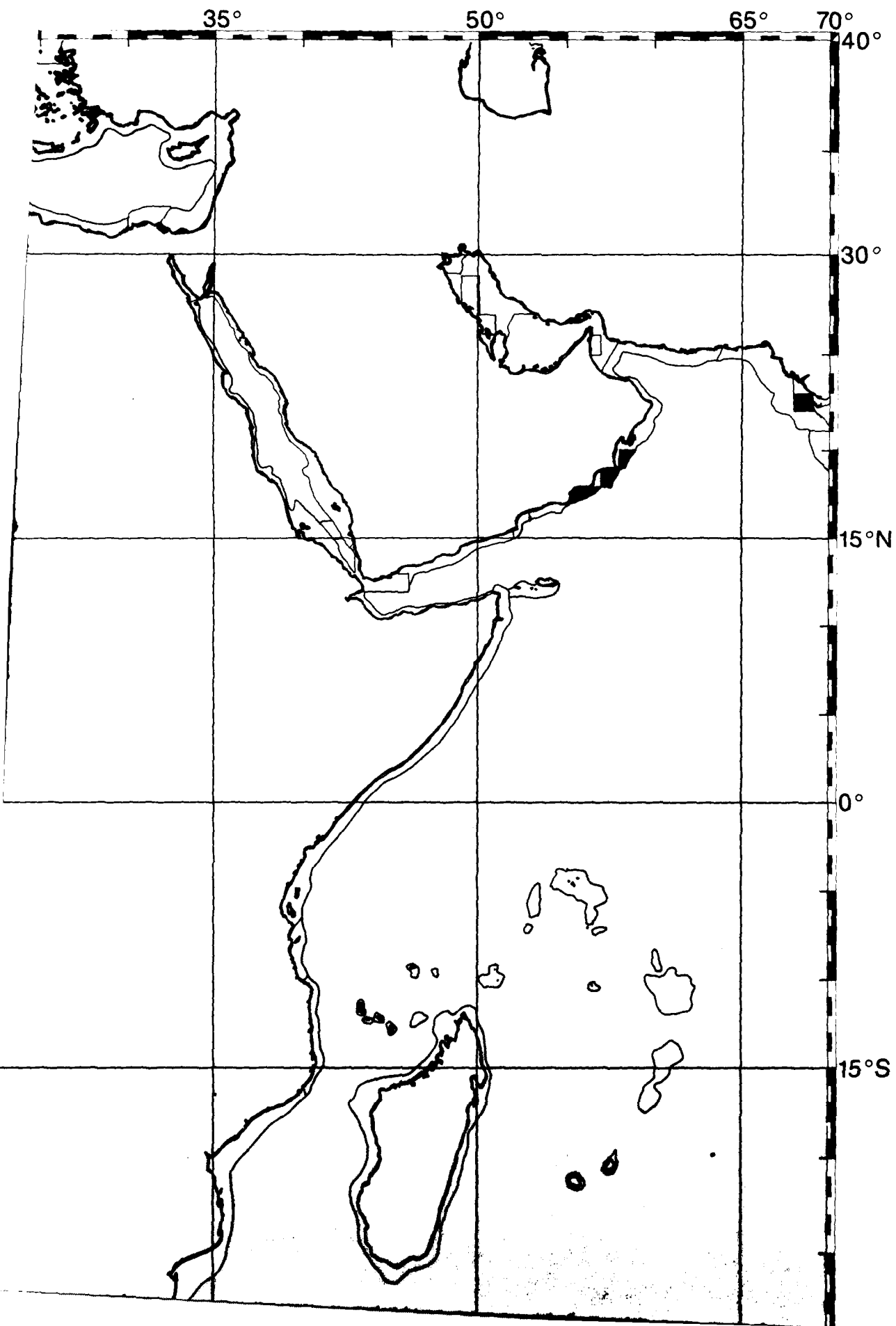


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TEMBER





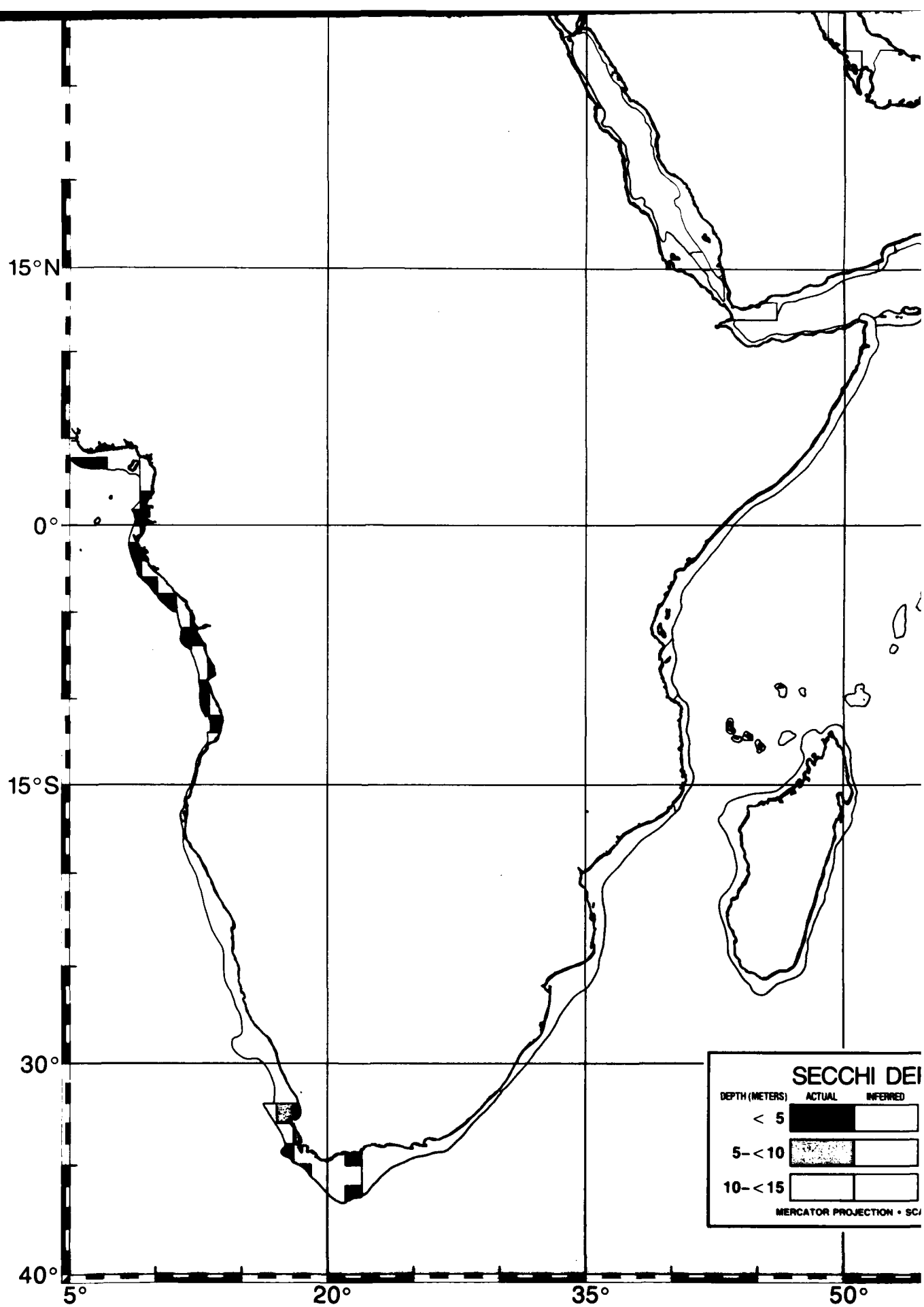
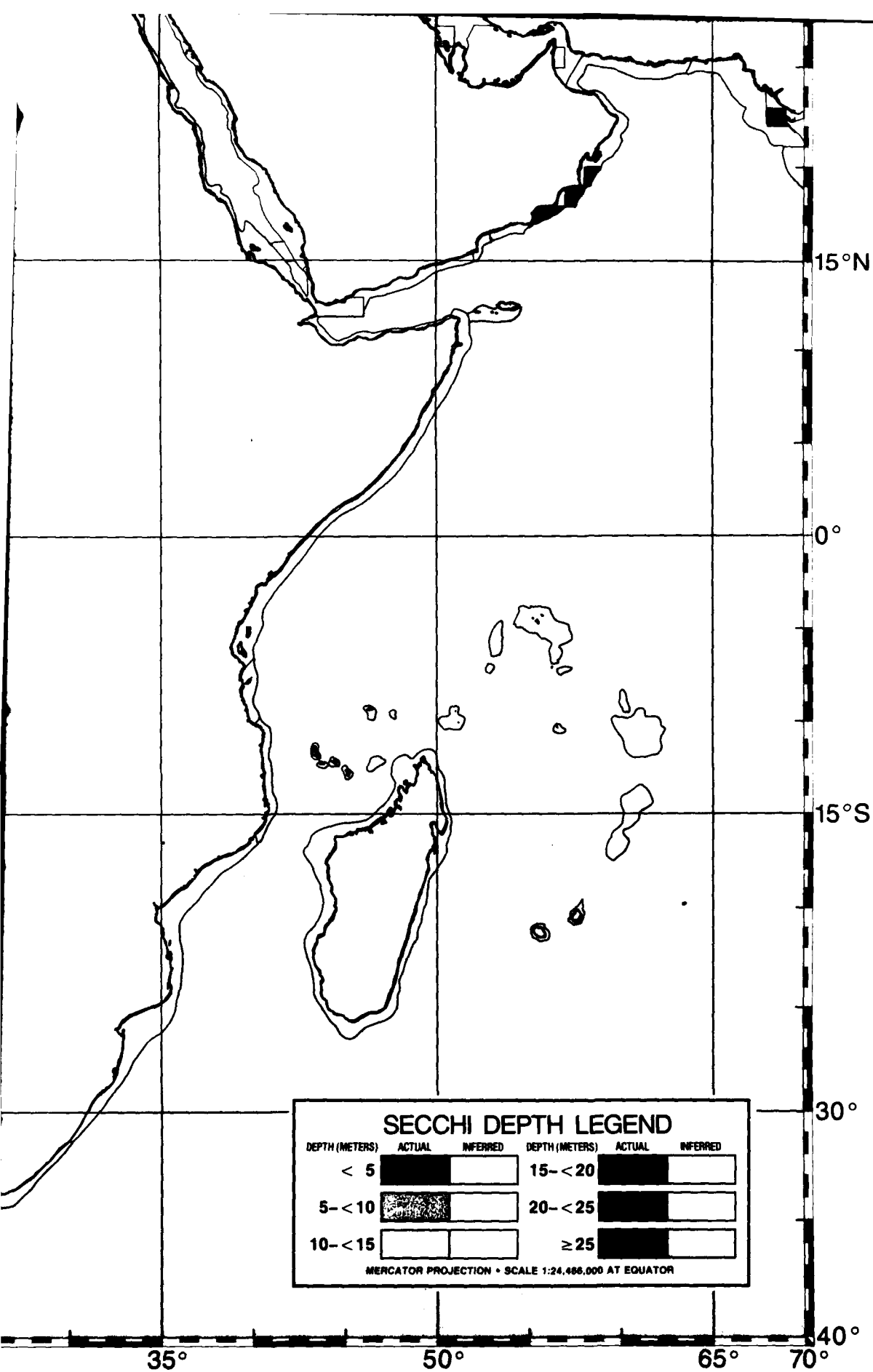
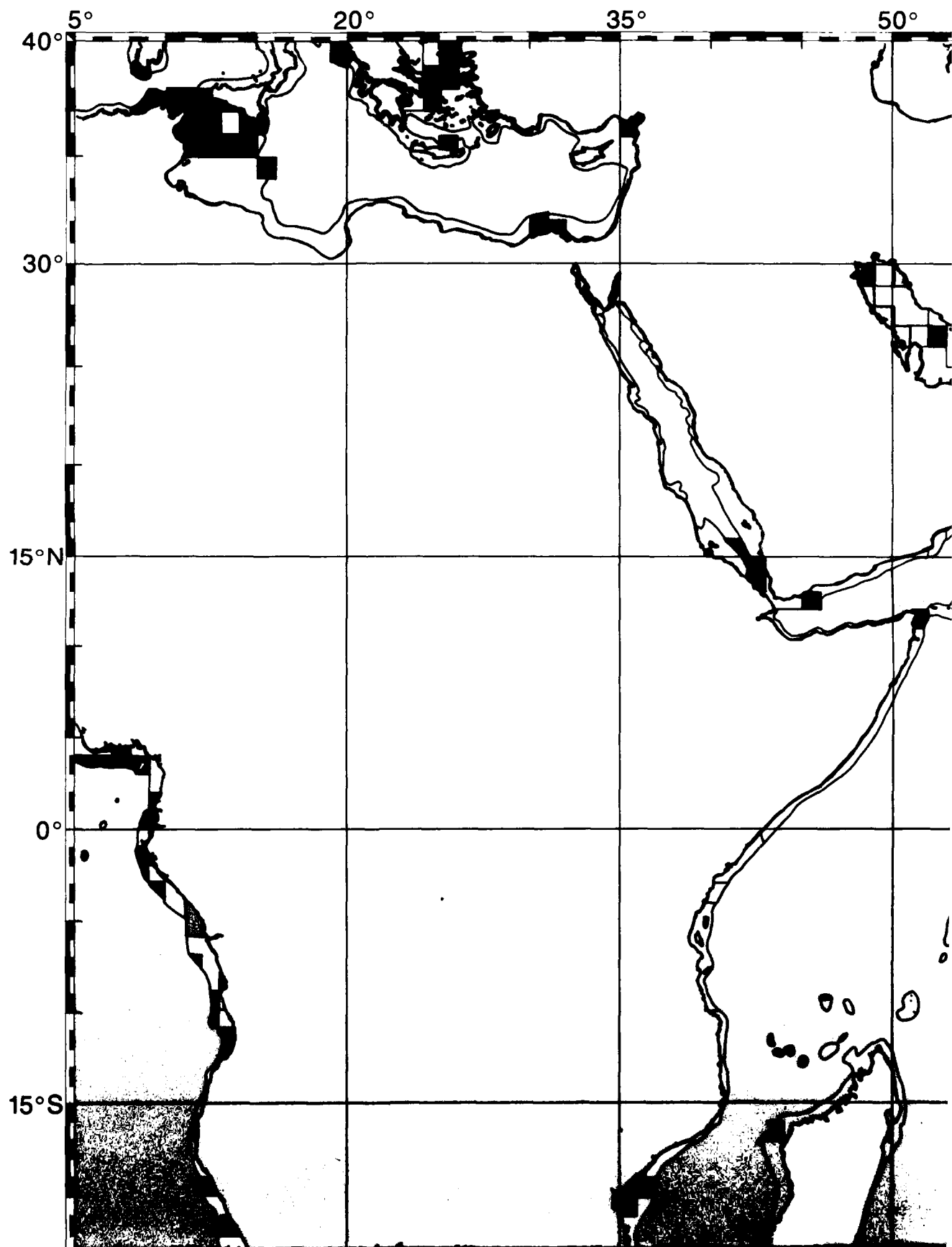


PLATE IX OCTOBER—DECEMBER

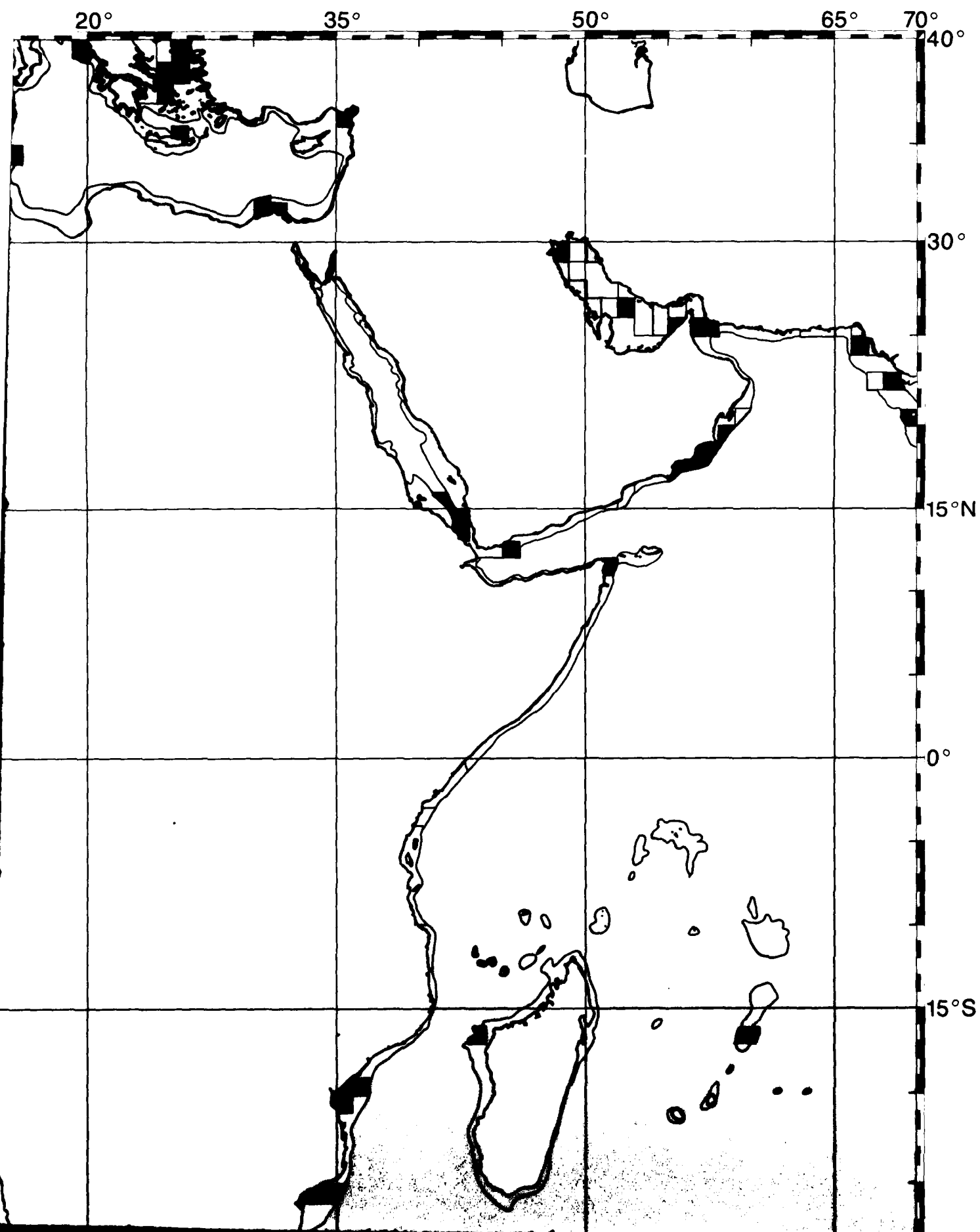


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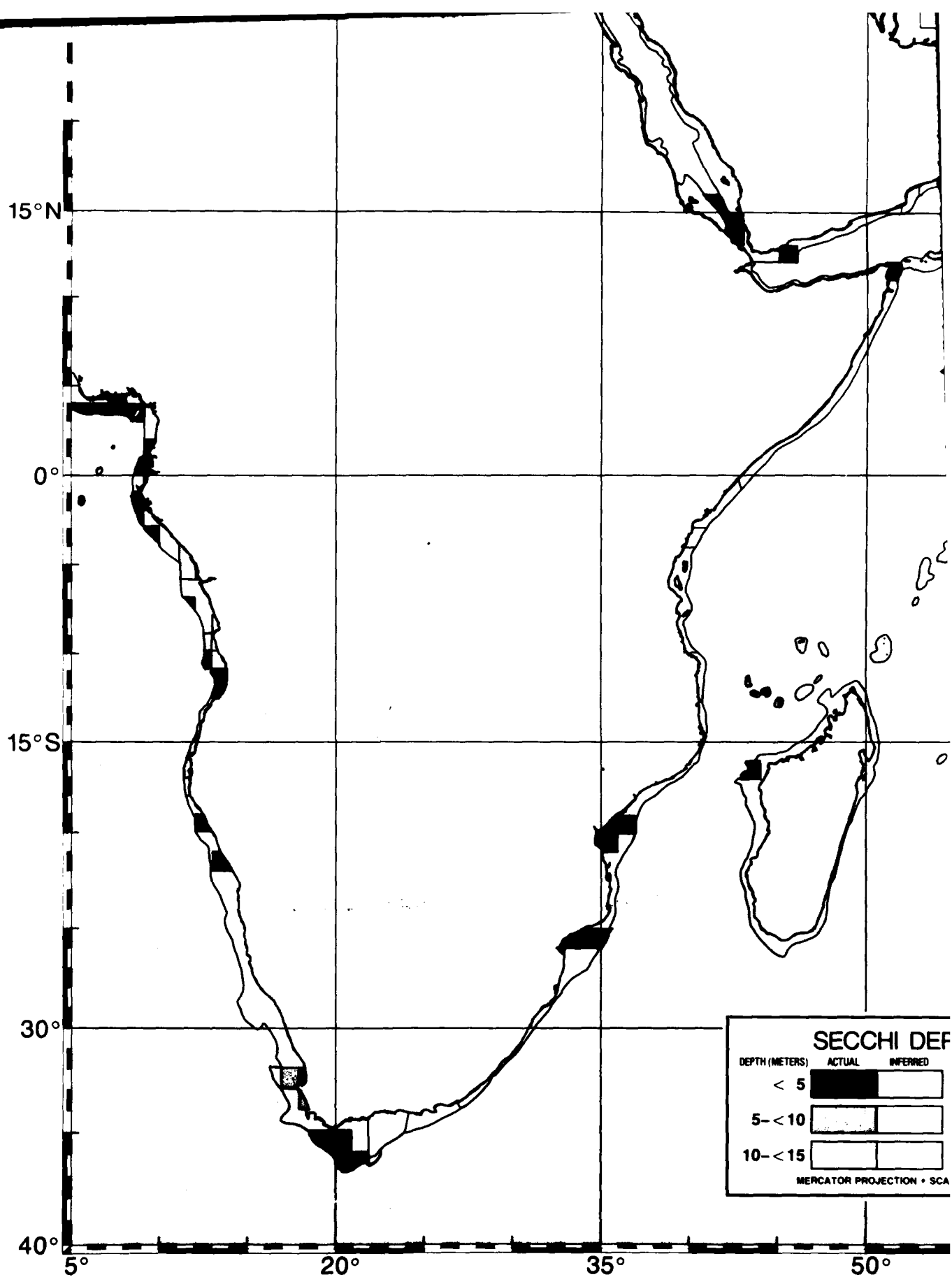
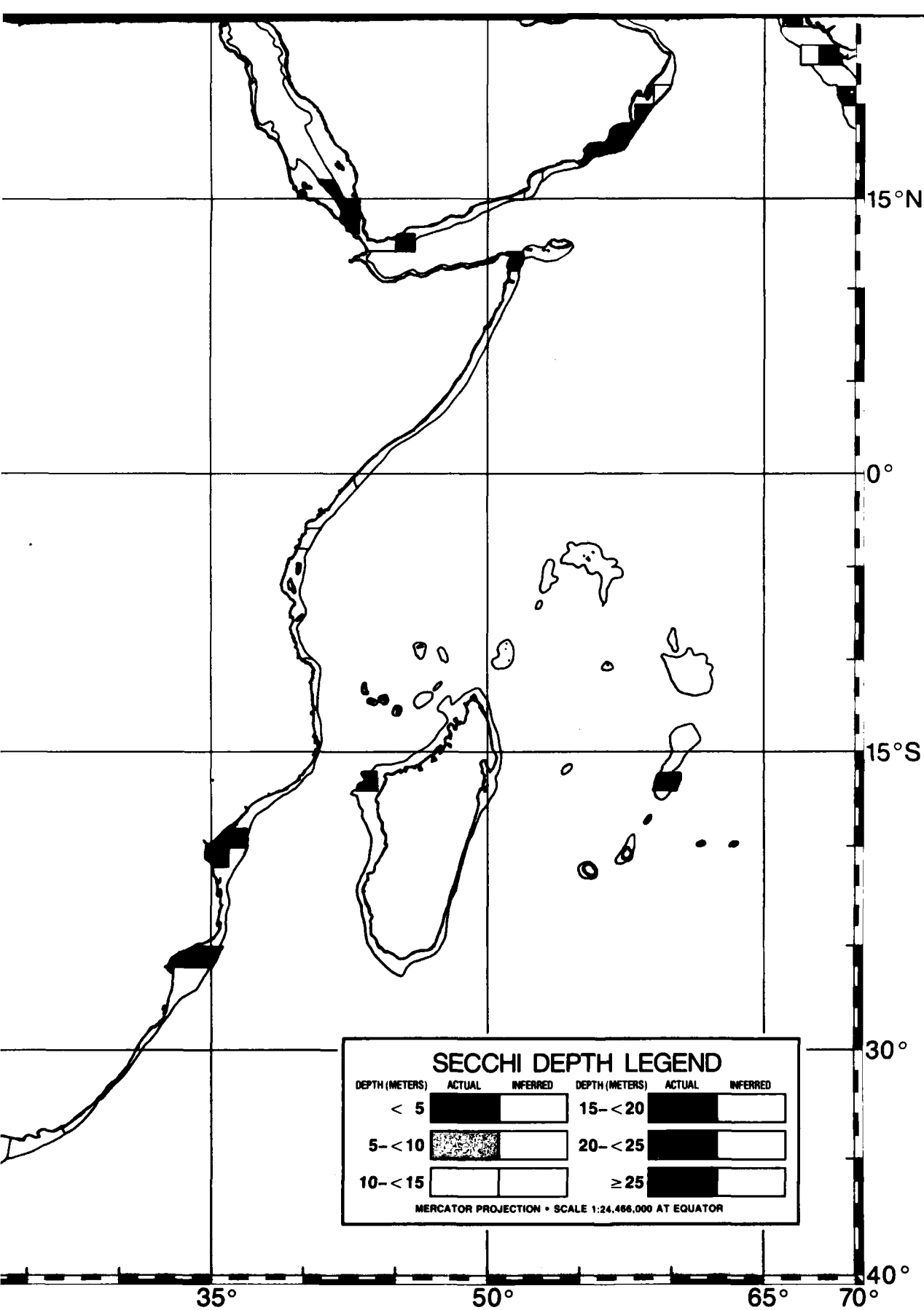
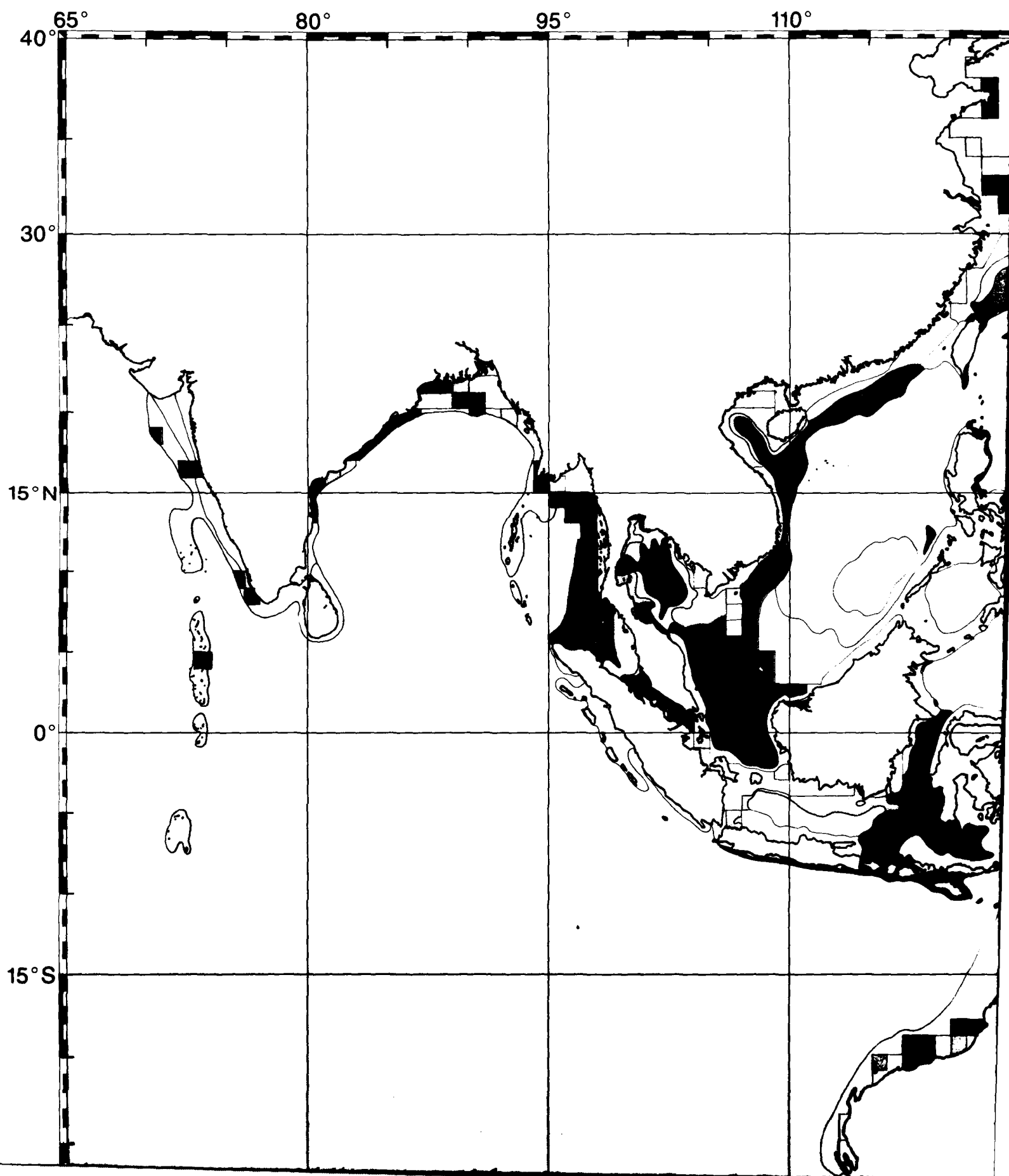


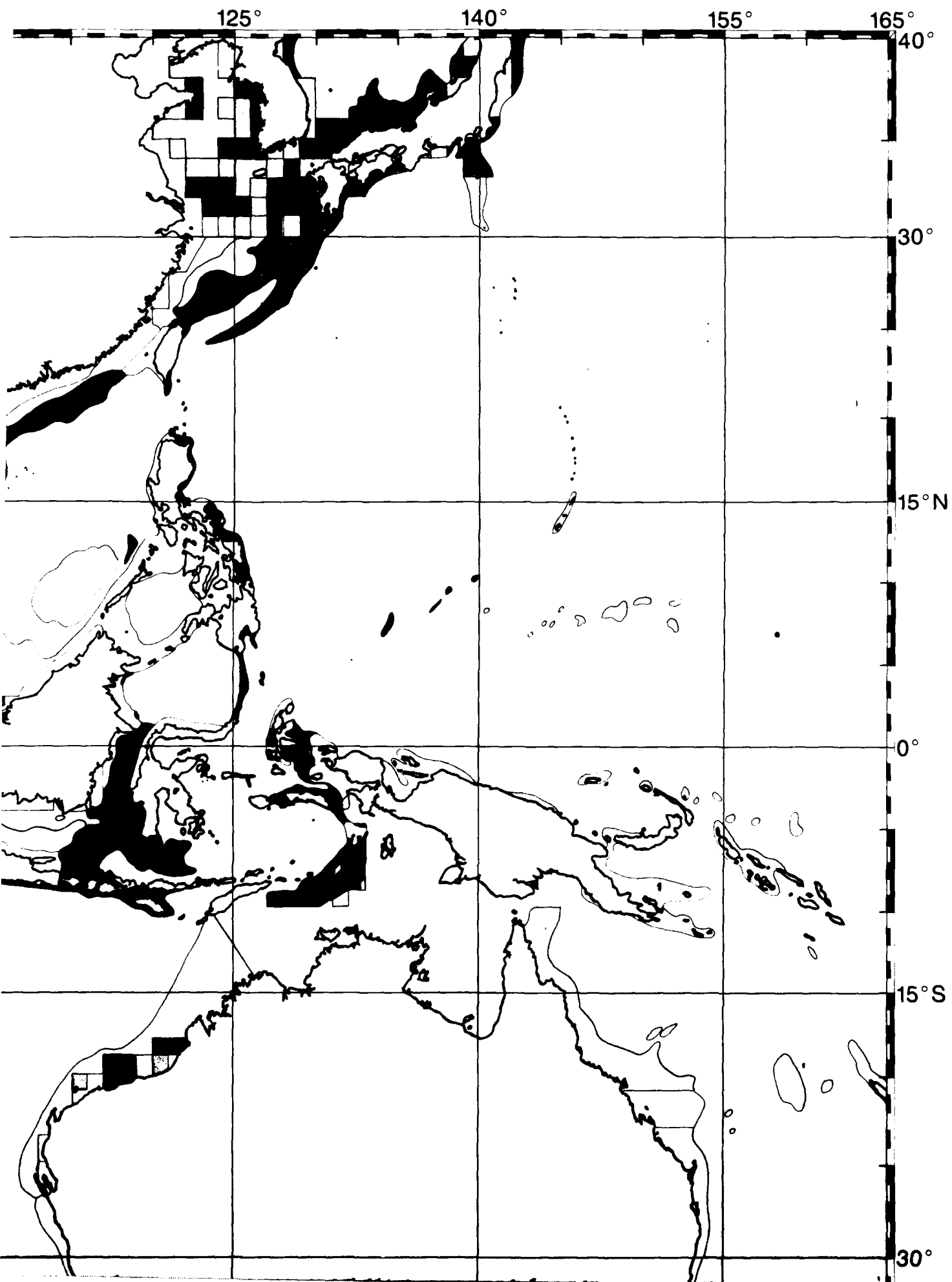
PLATE X ANNUAL MEAN

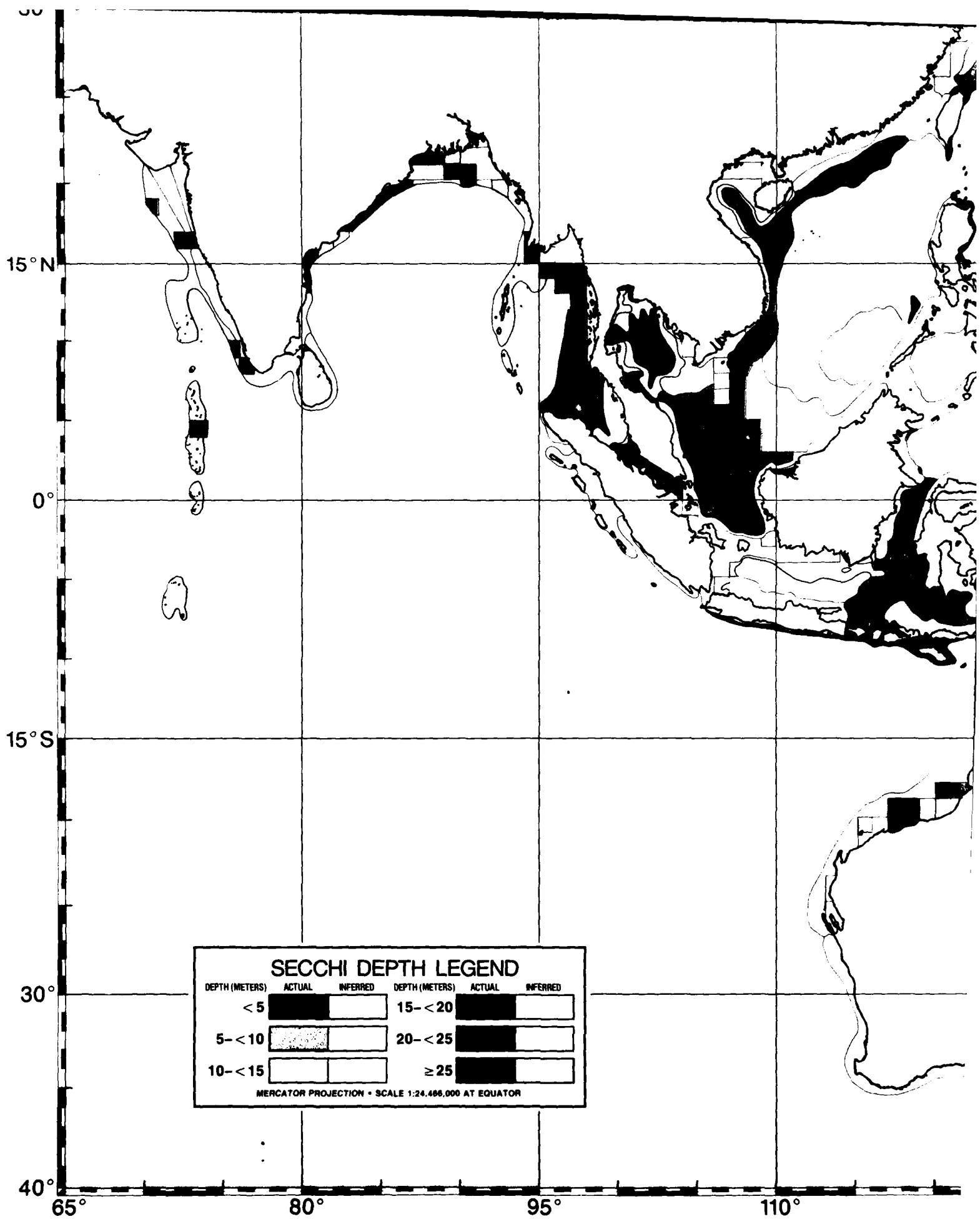


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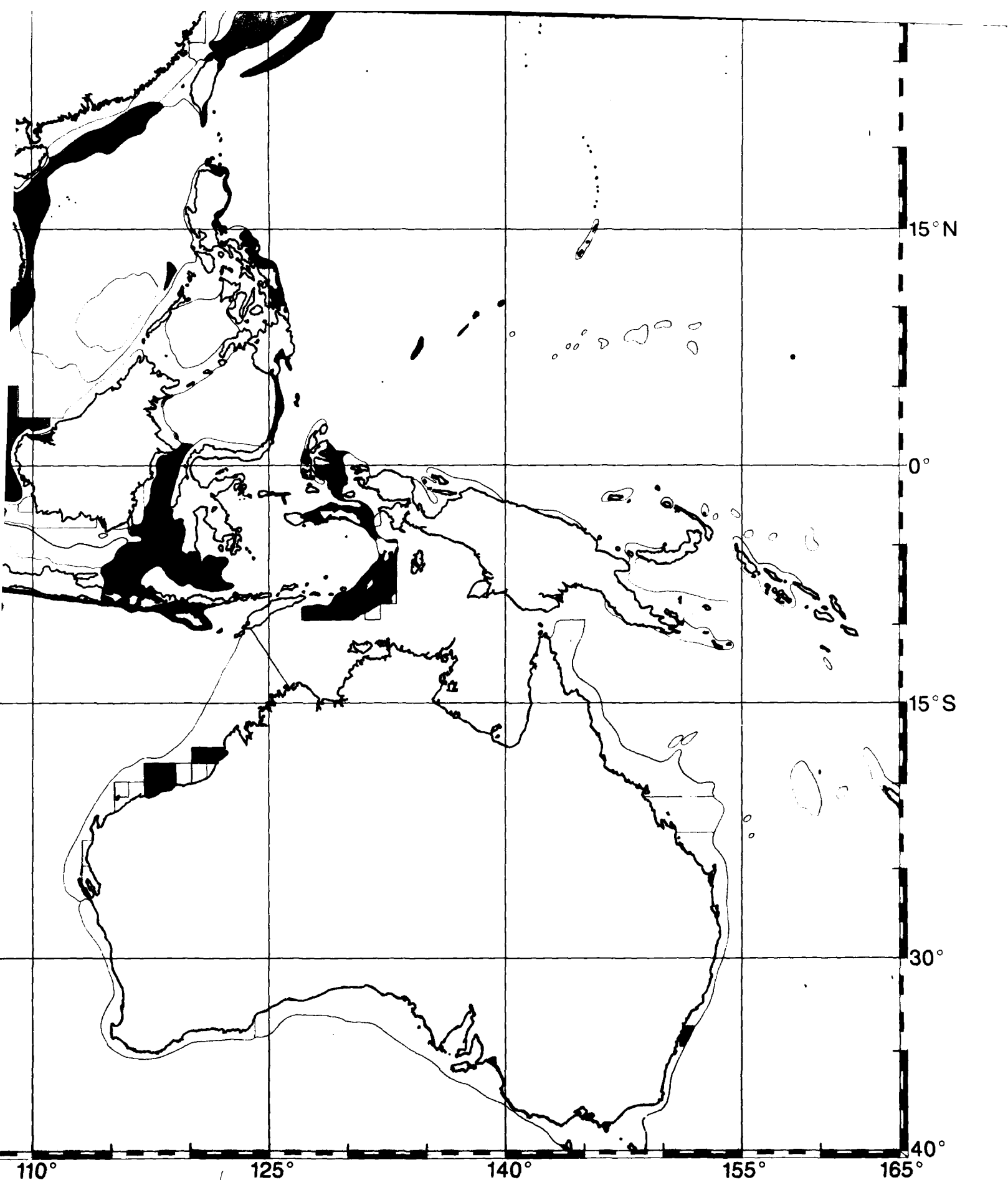






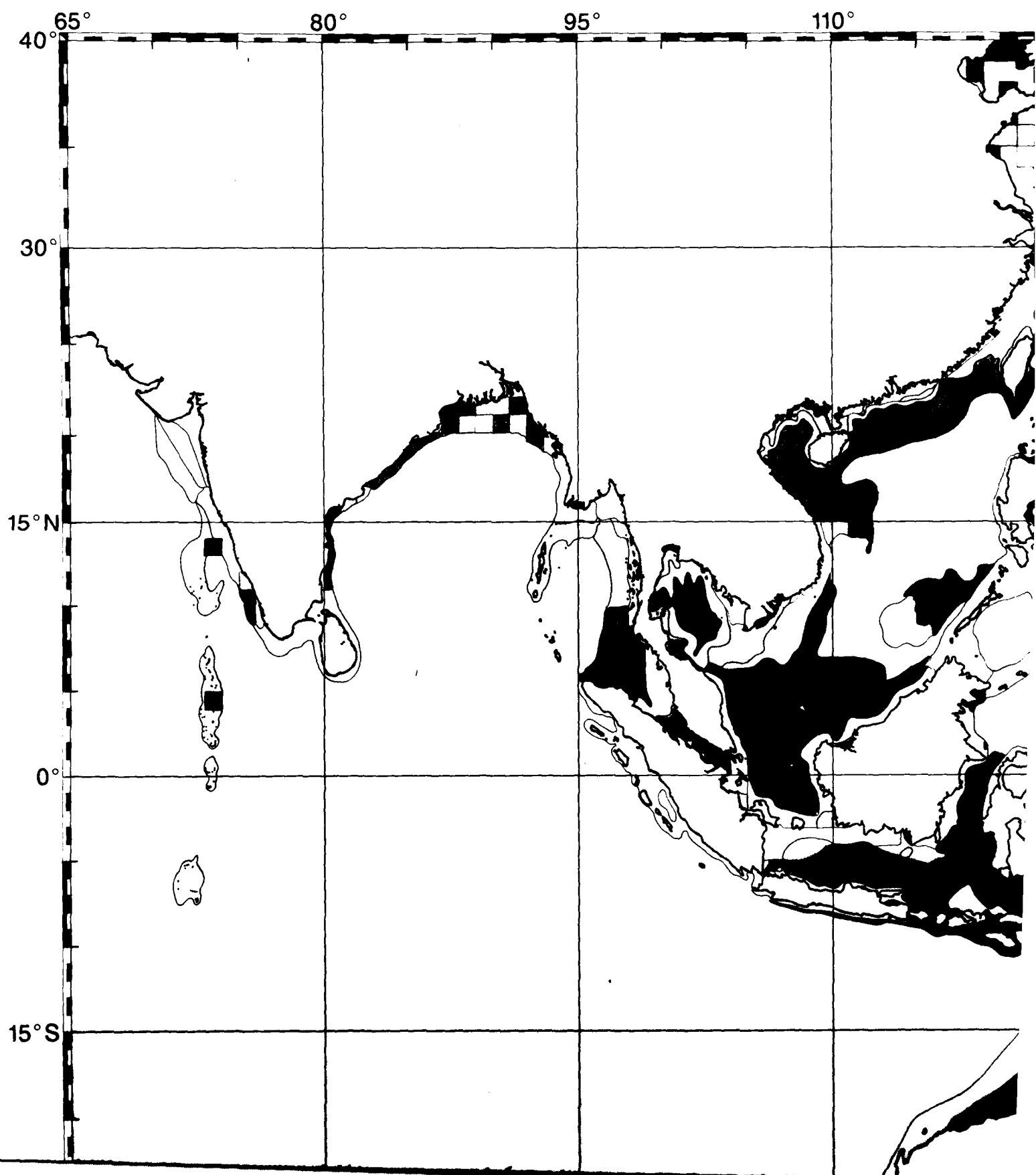


**PLATE XI JANUARY—MARCH**

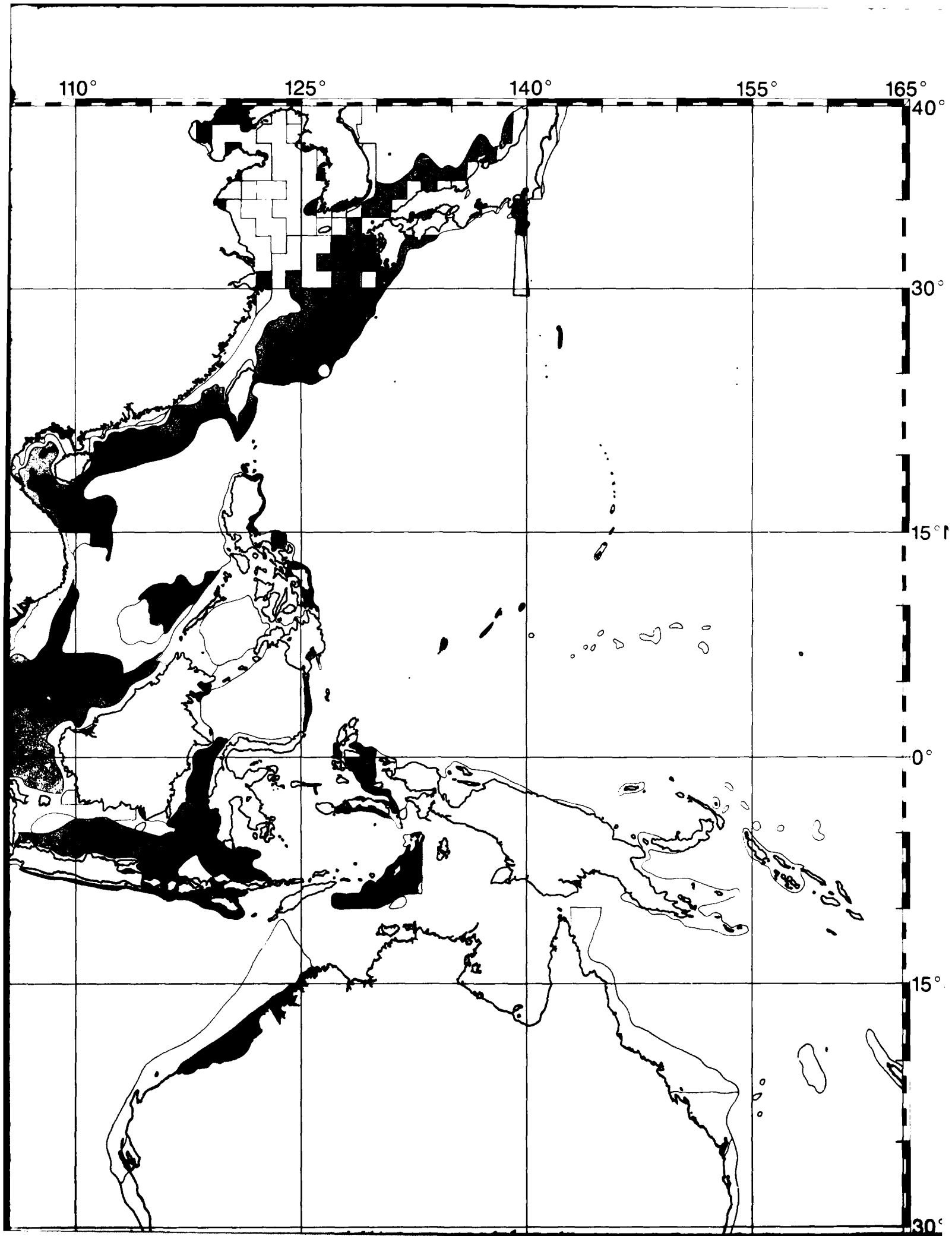


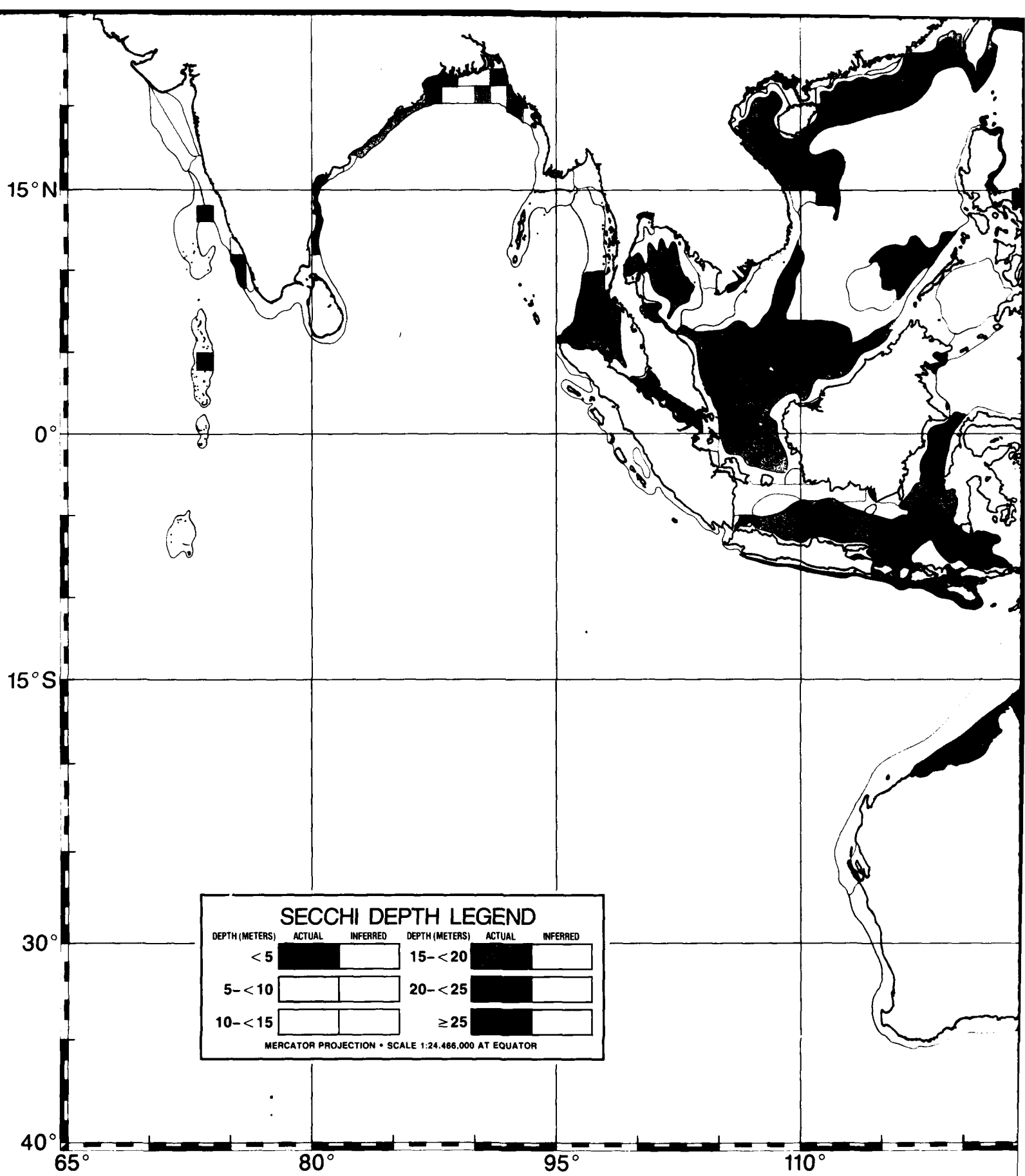
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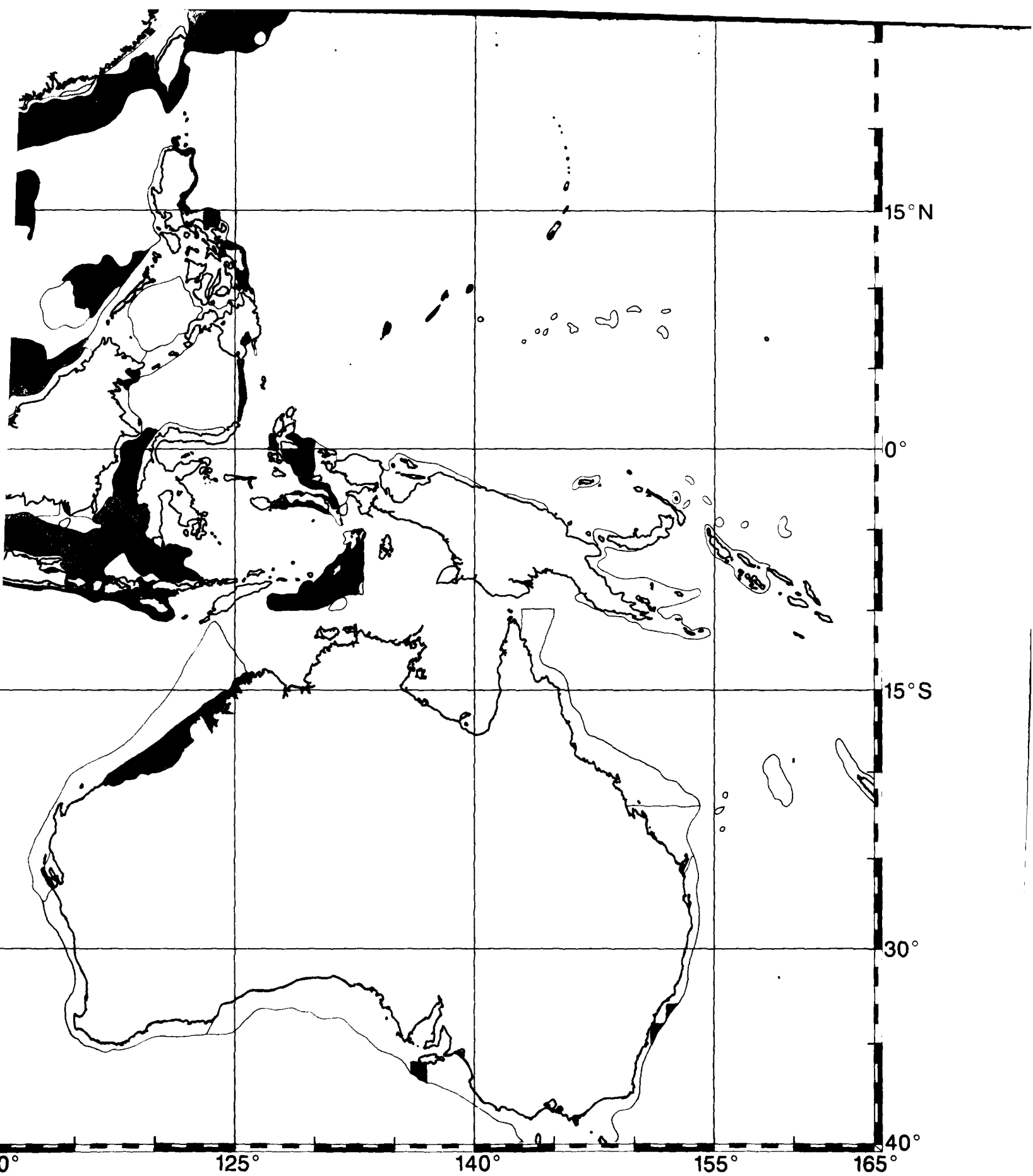






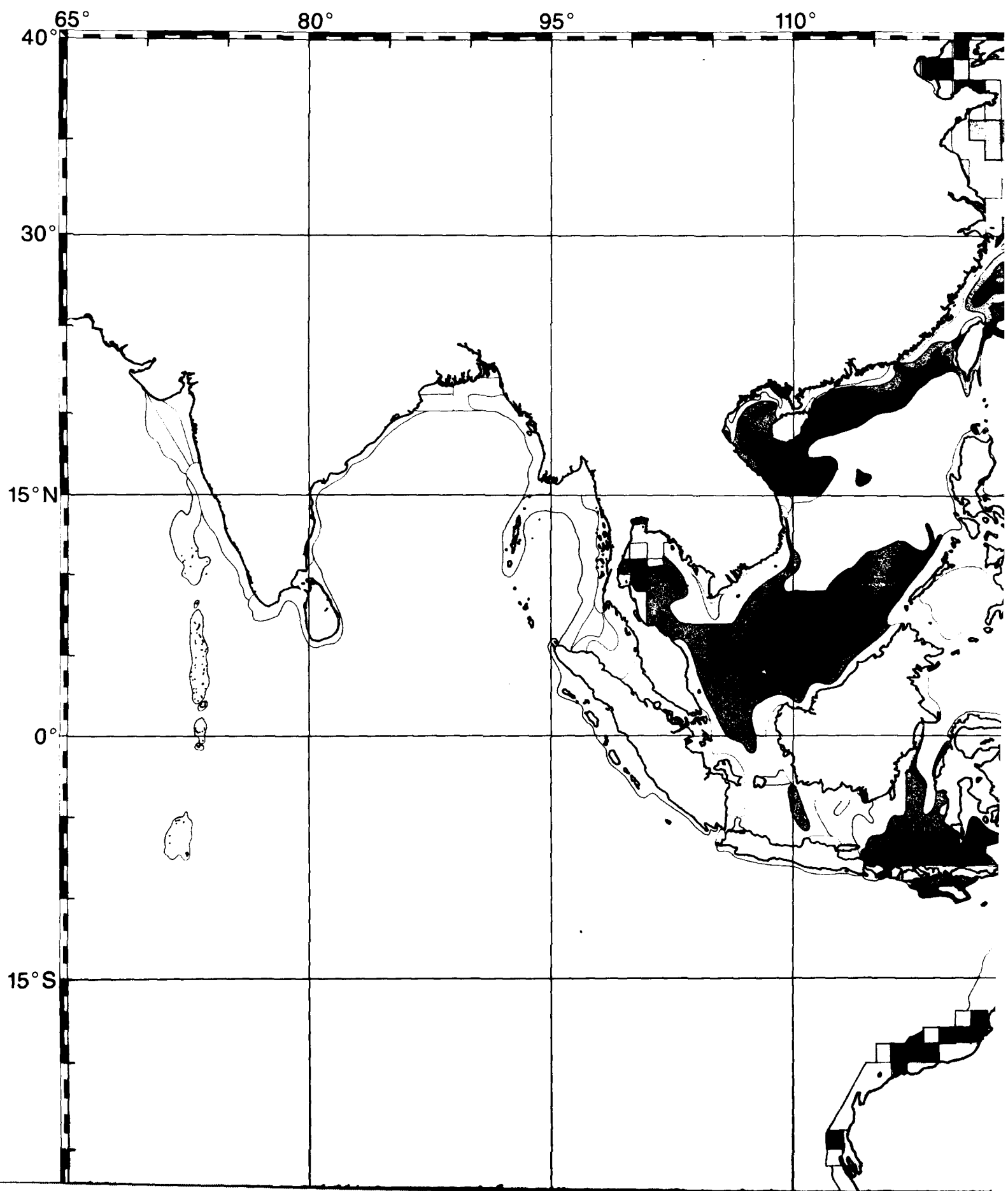


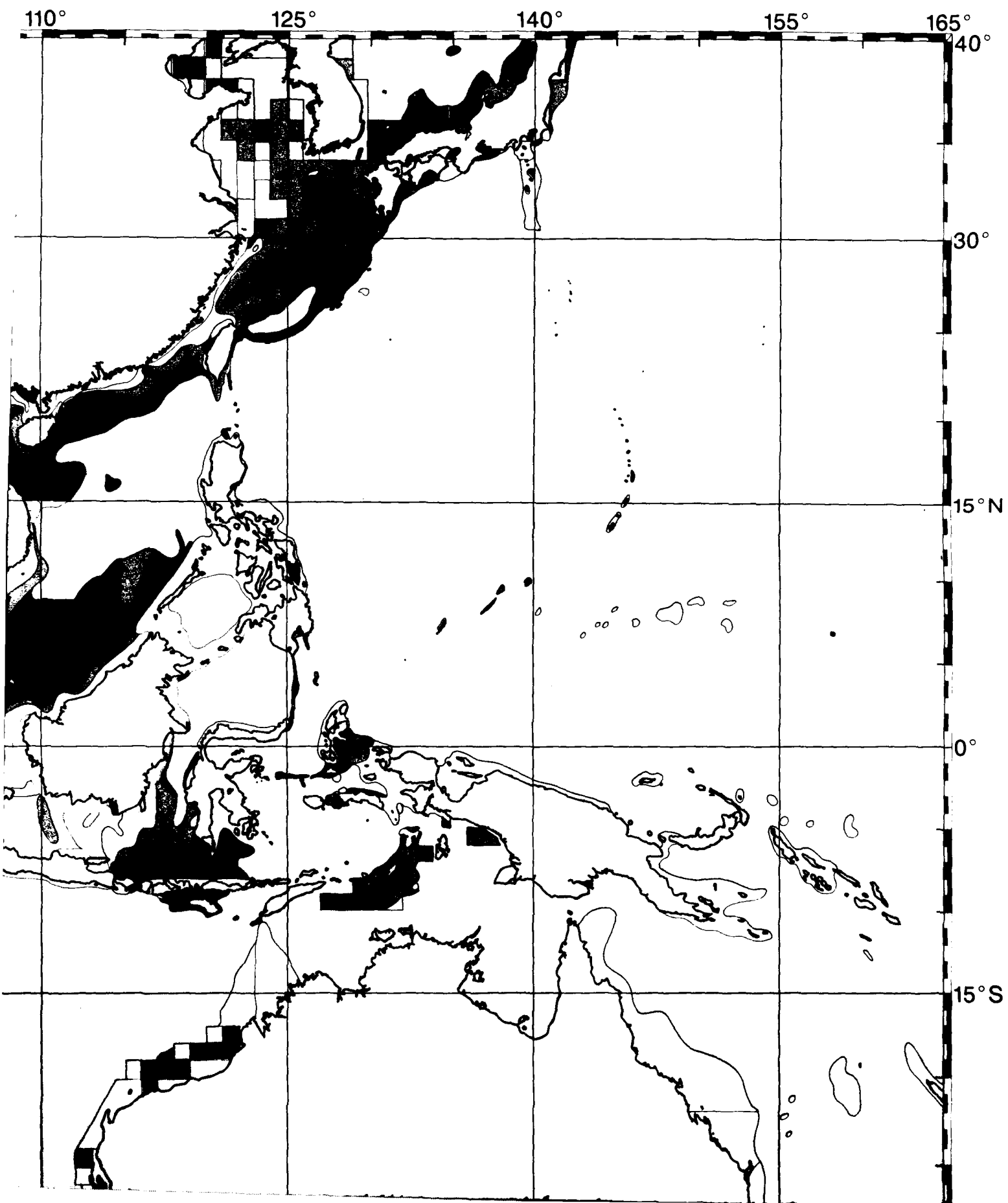
**PLATE XII APRIL—JUNE**



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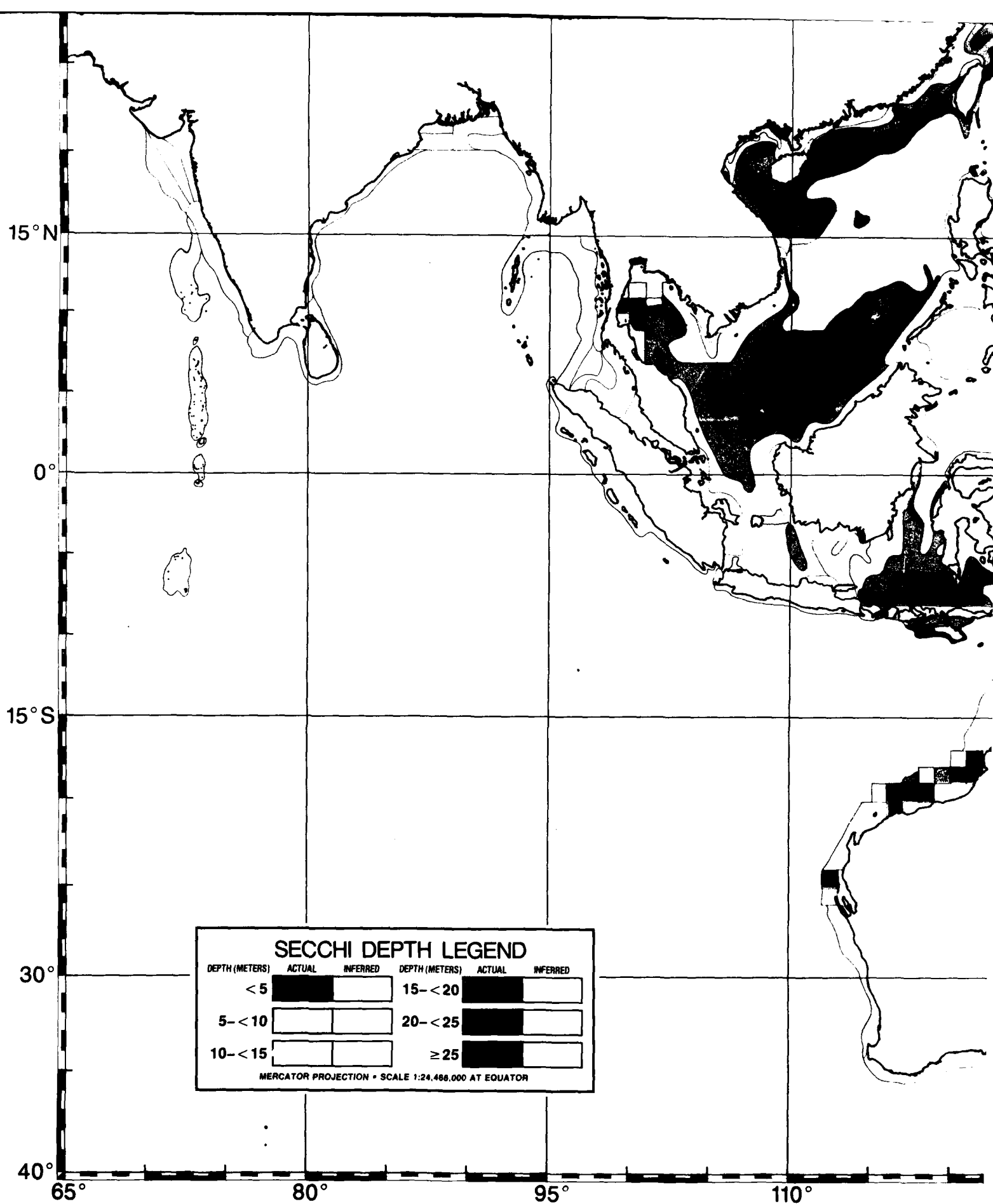
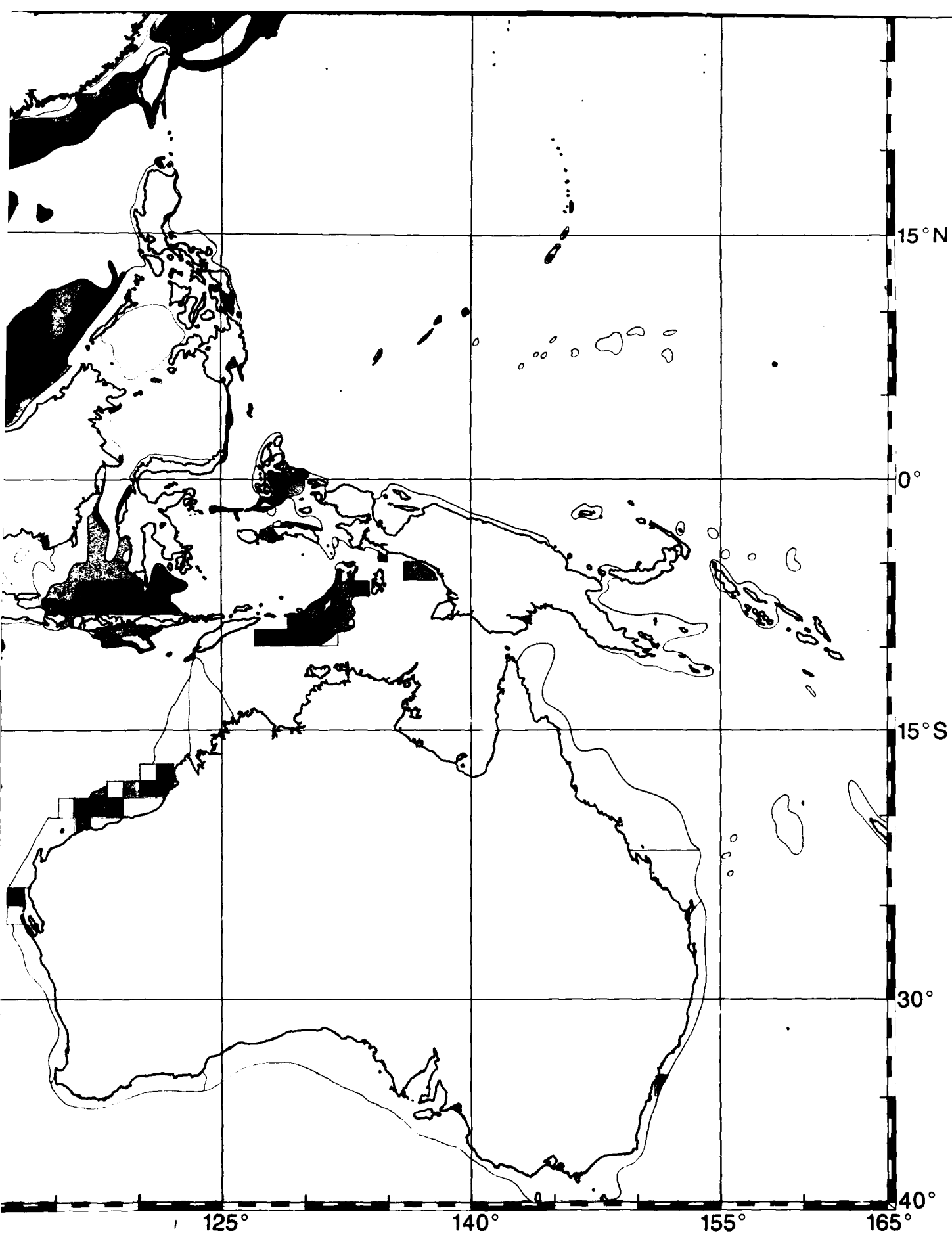


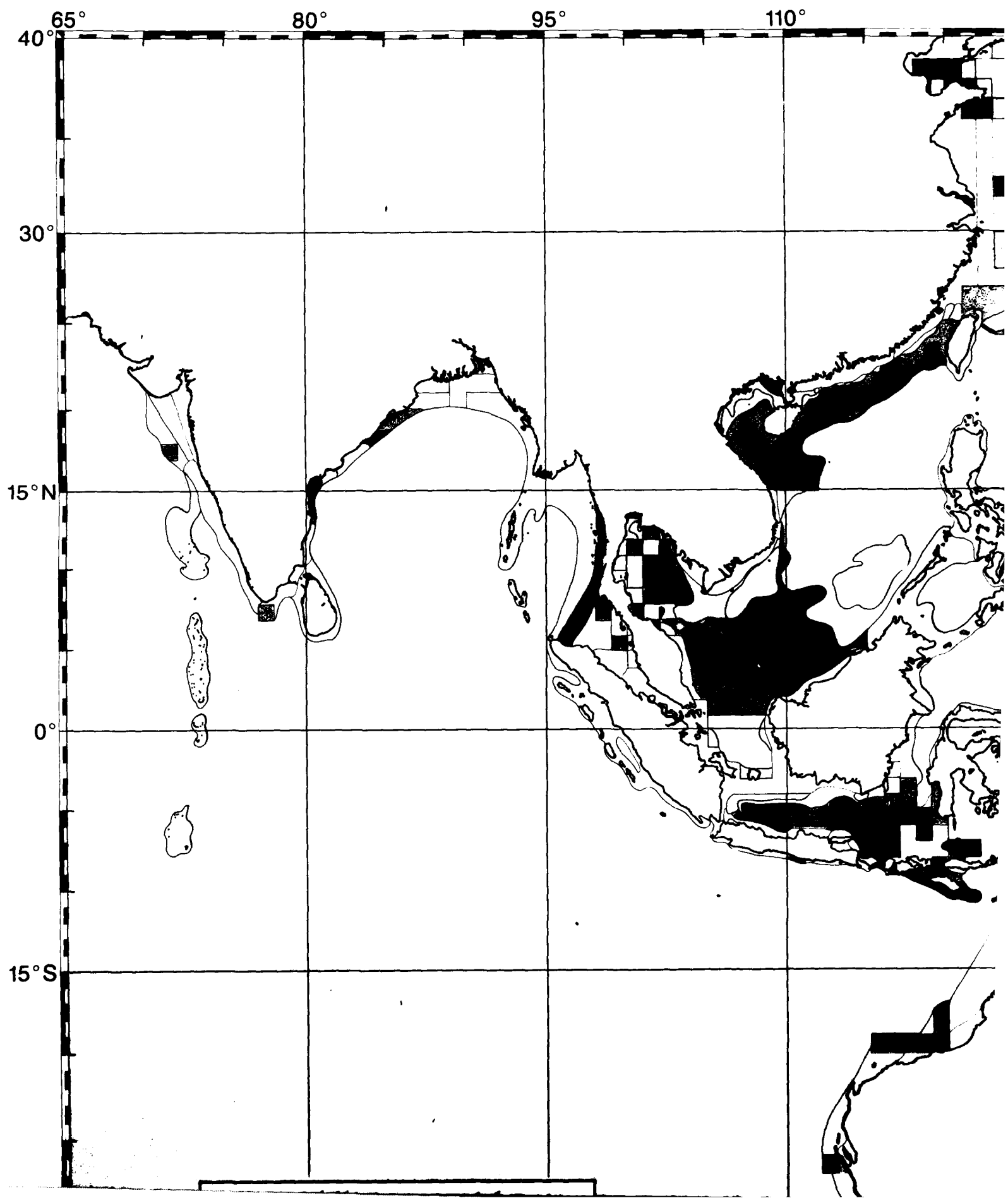
PLATE XIII JULY-SEPTEMBER



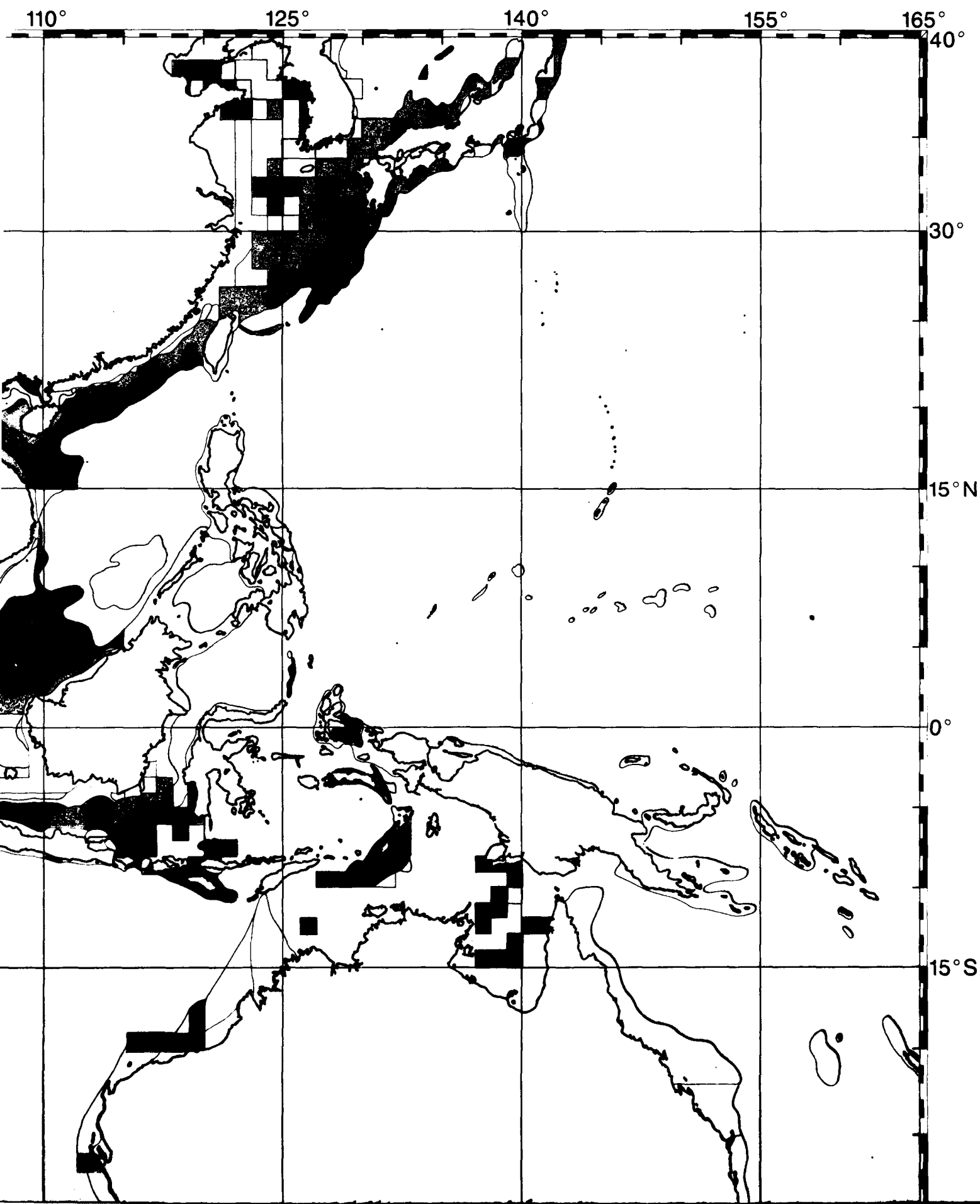
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3







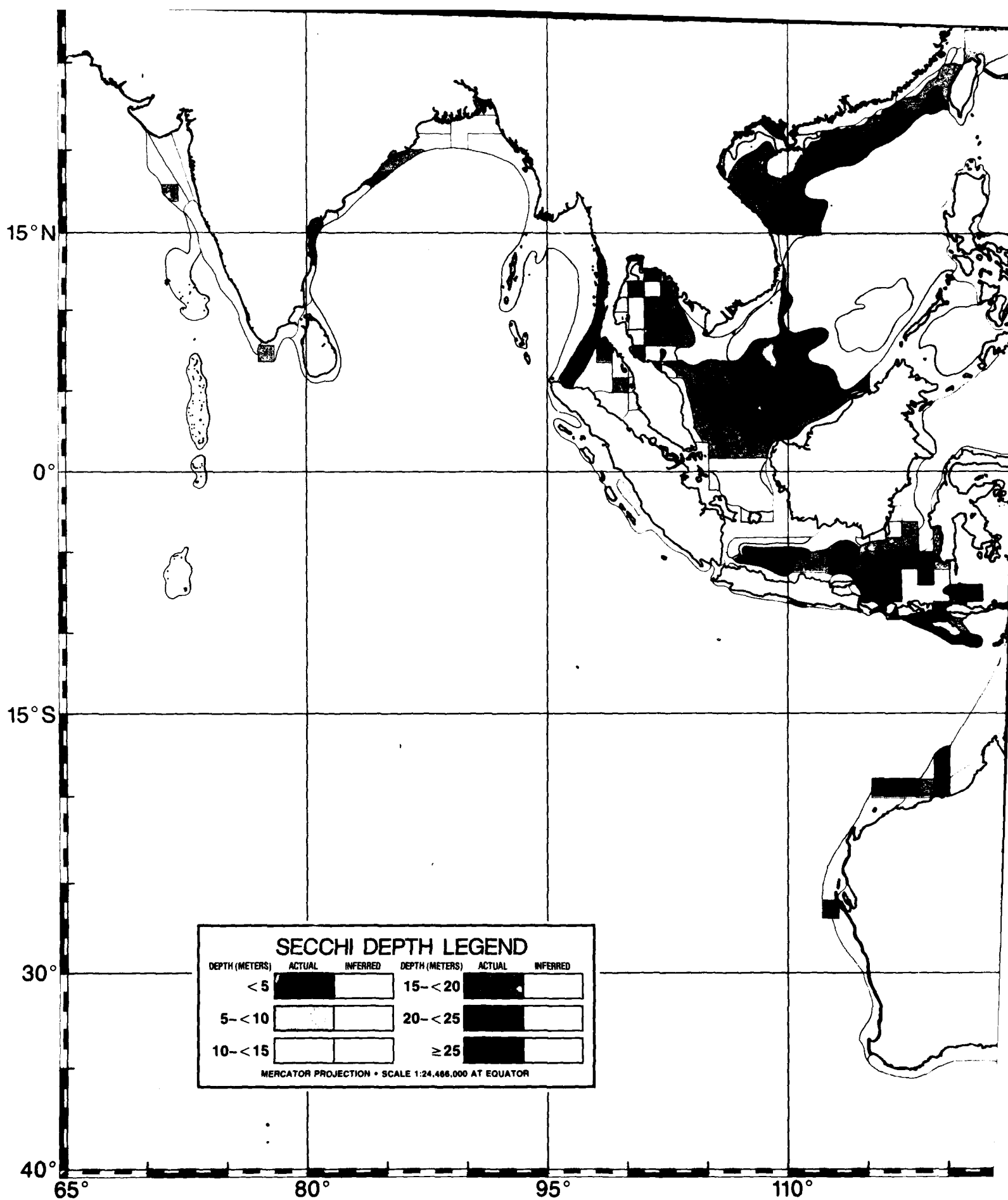
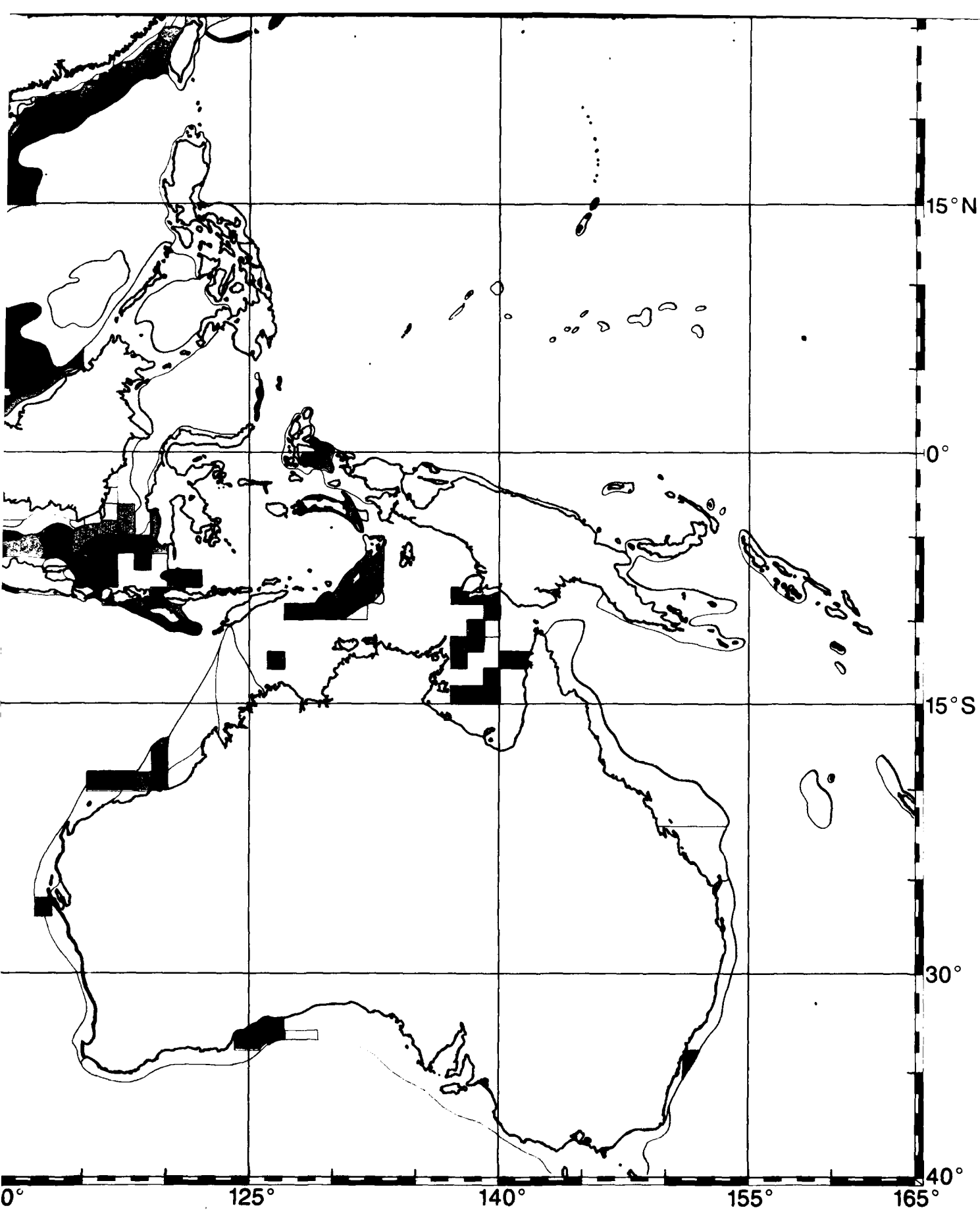
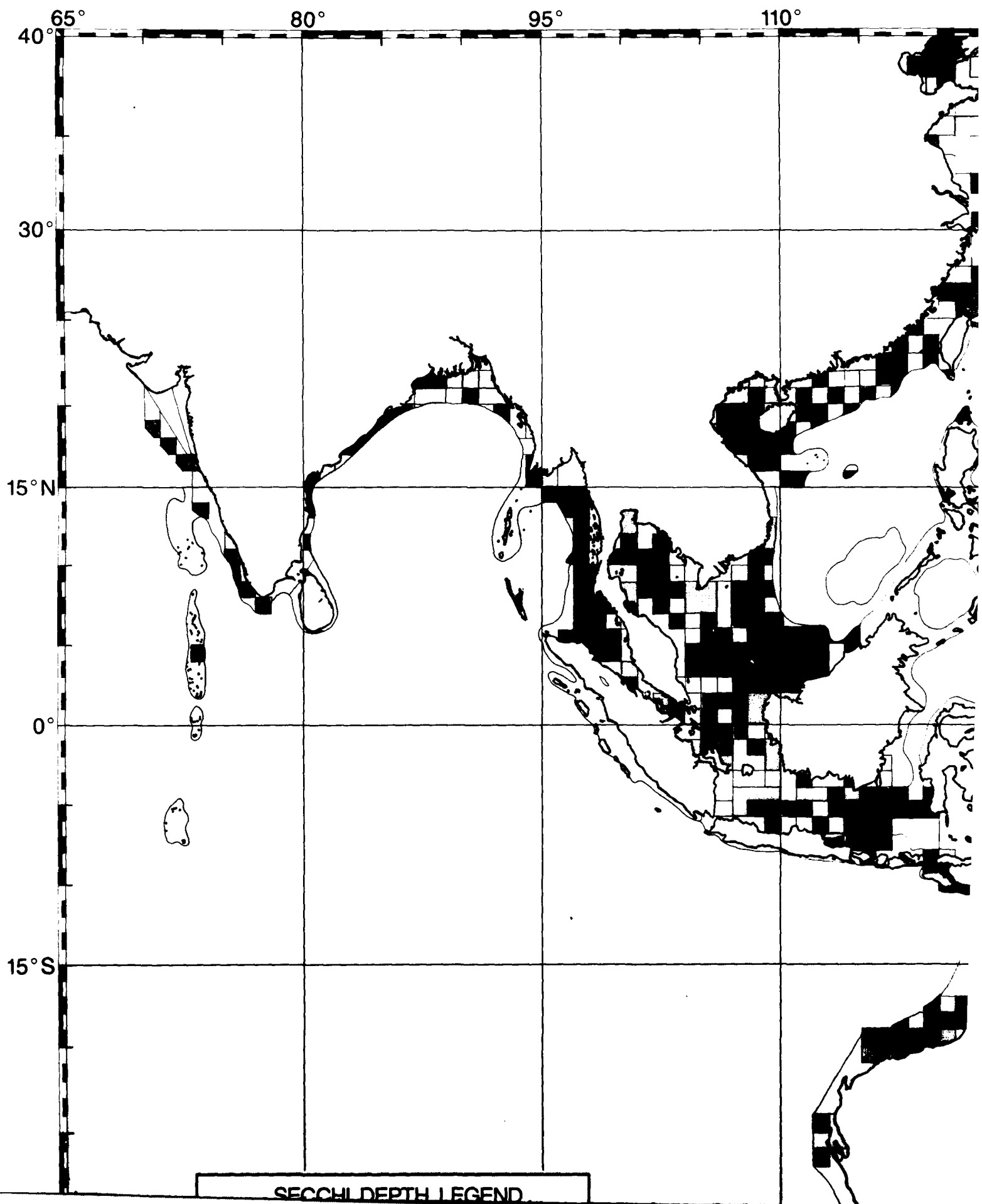


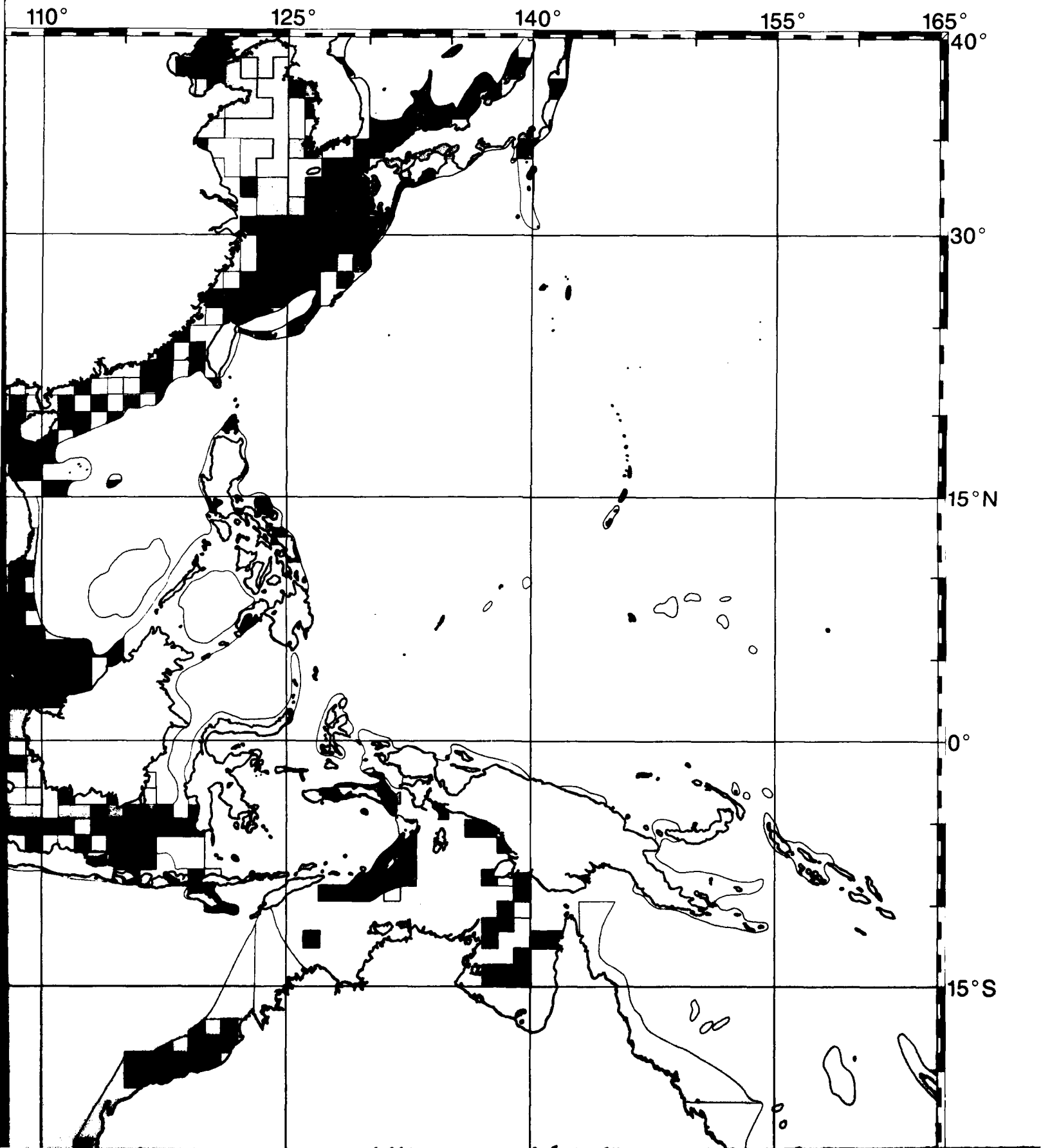
PLATE XIV OCTOBER—DECEMBER



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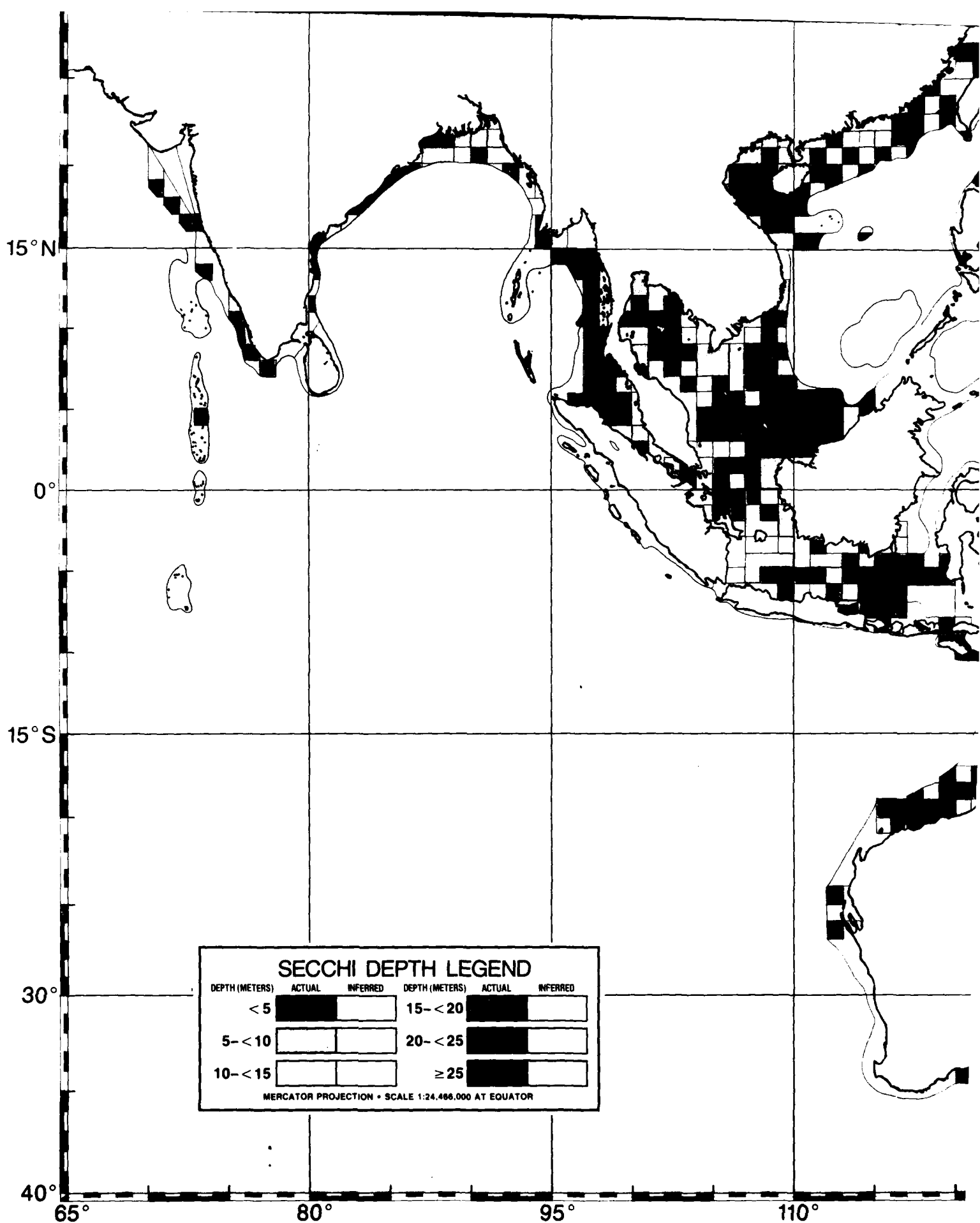
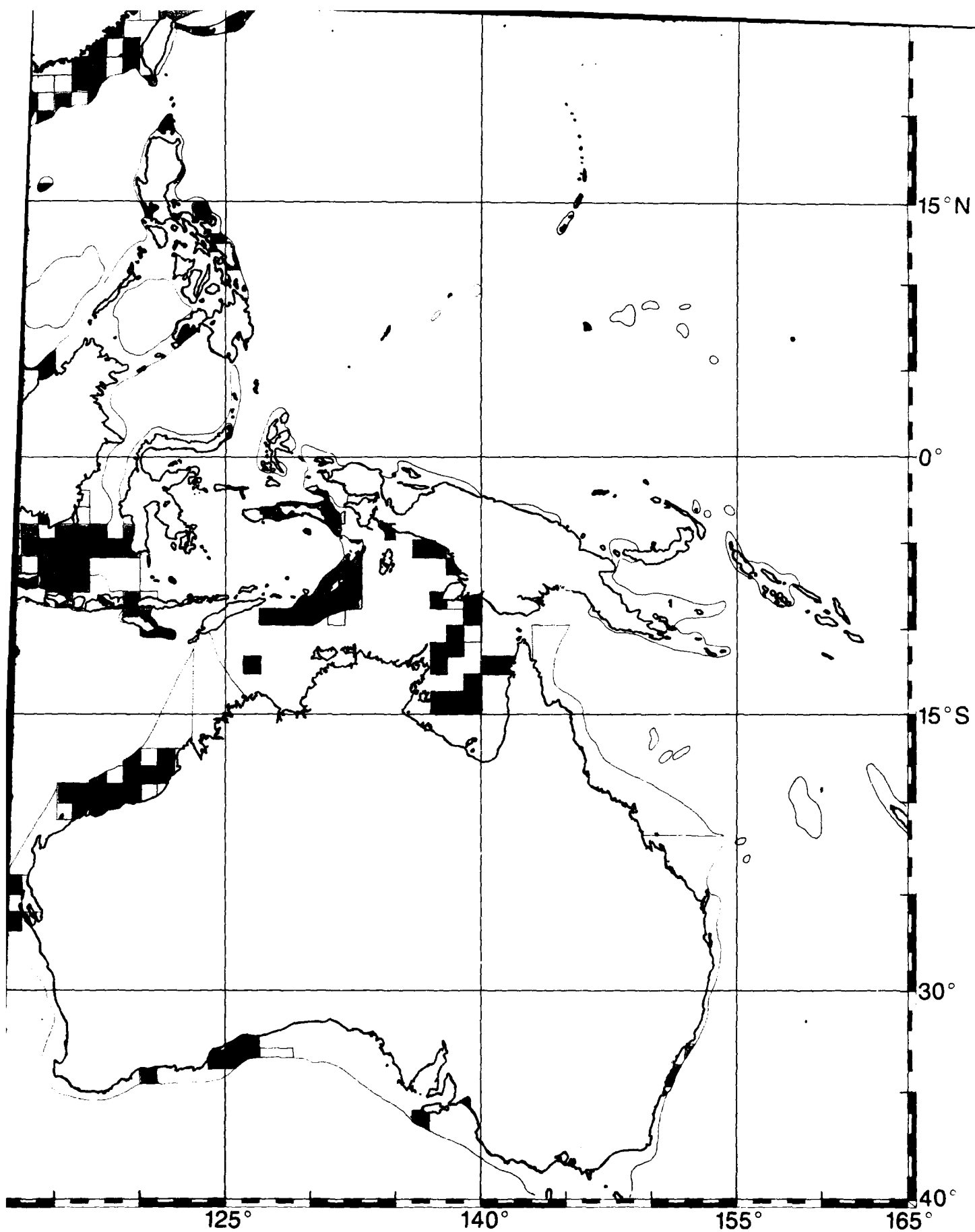
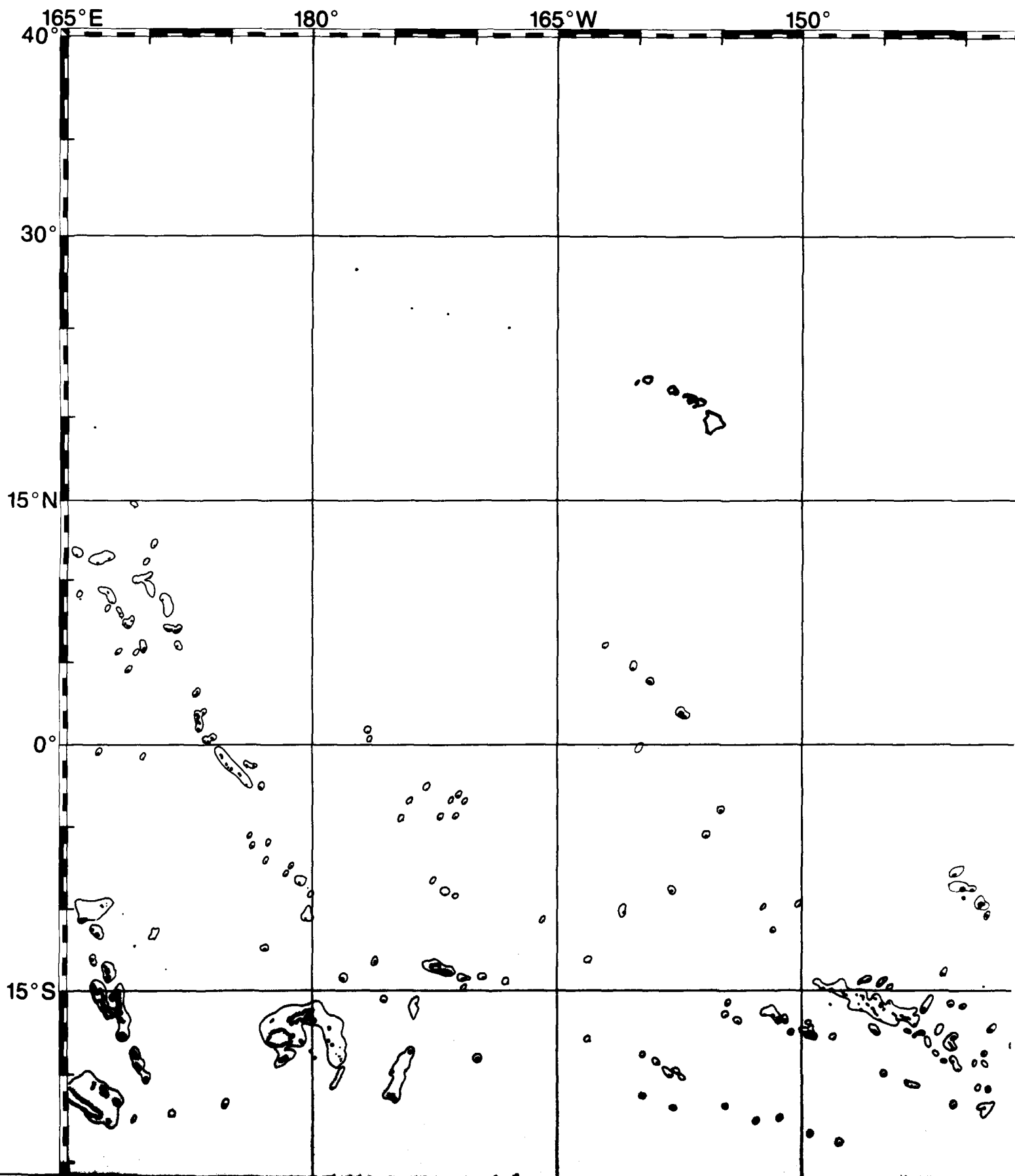


PLATE XV ANNUAL MEAN

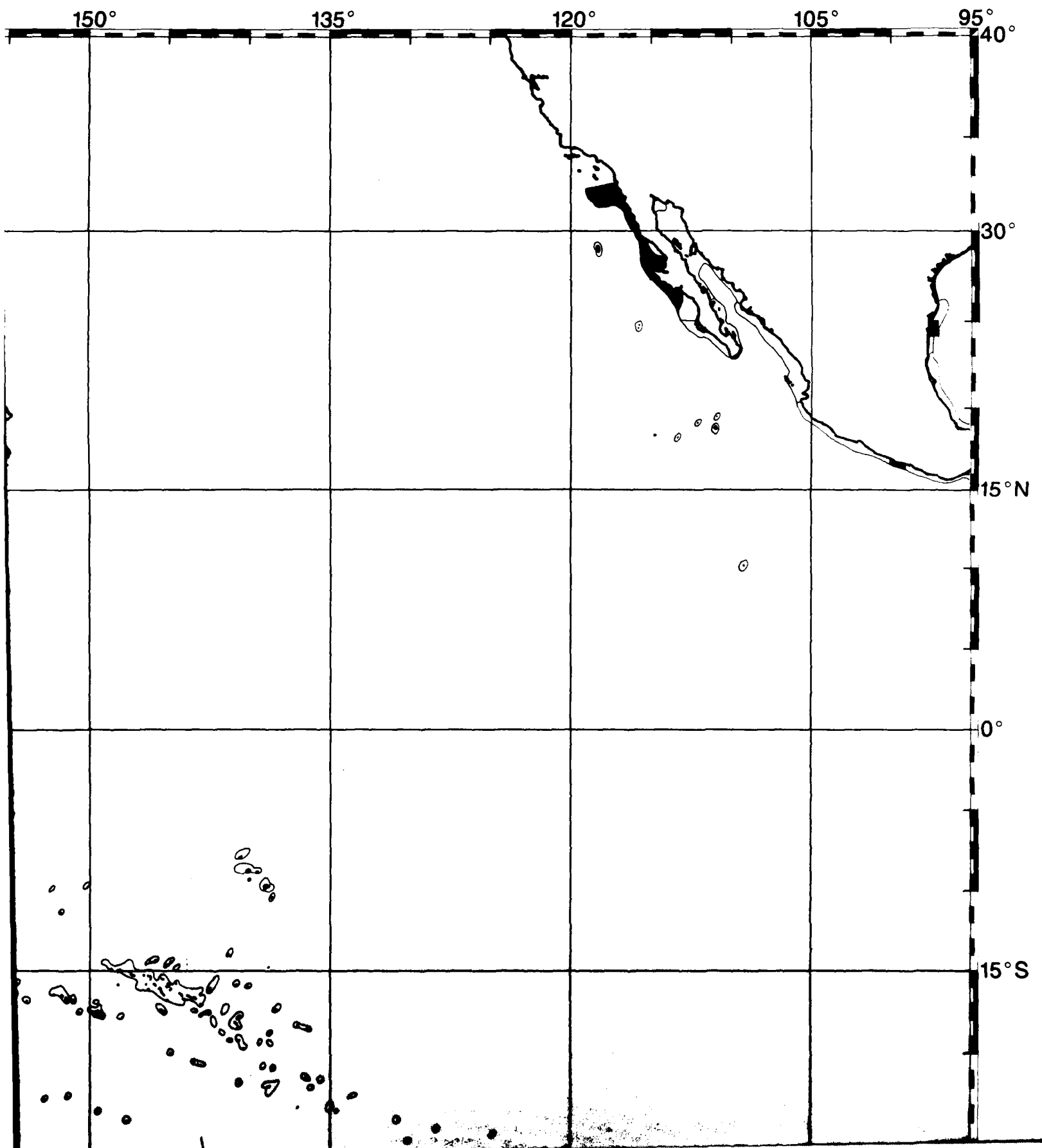


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15°N

0°

15°S

30°

40°

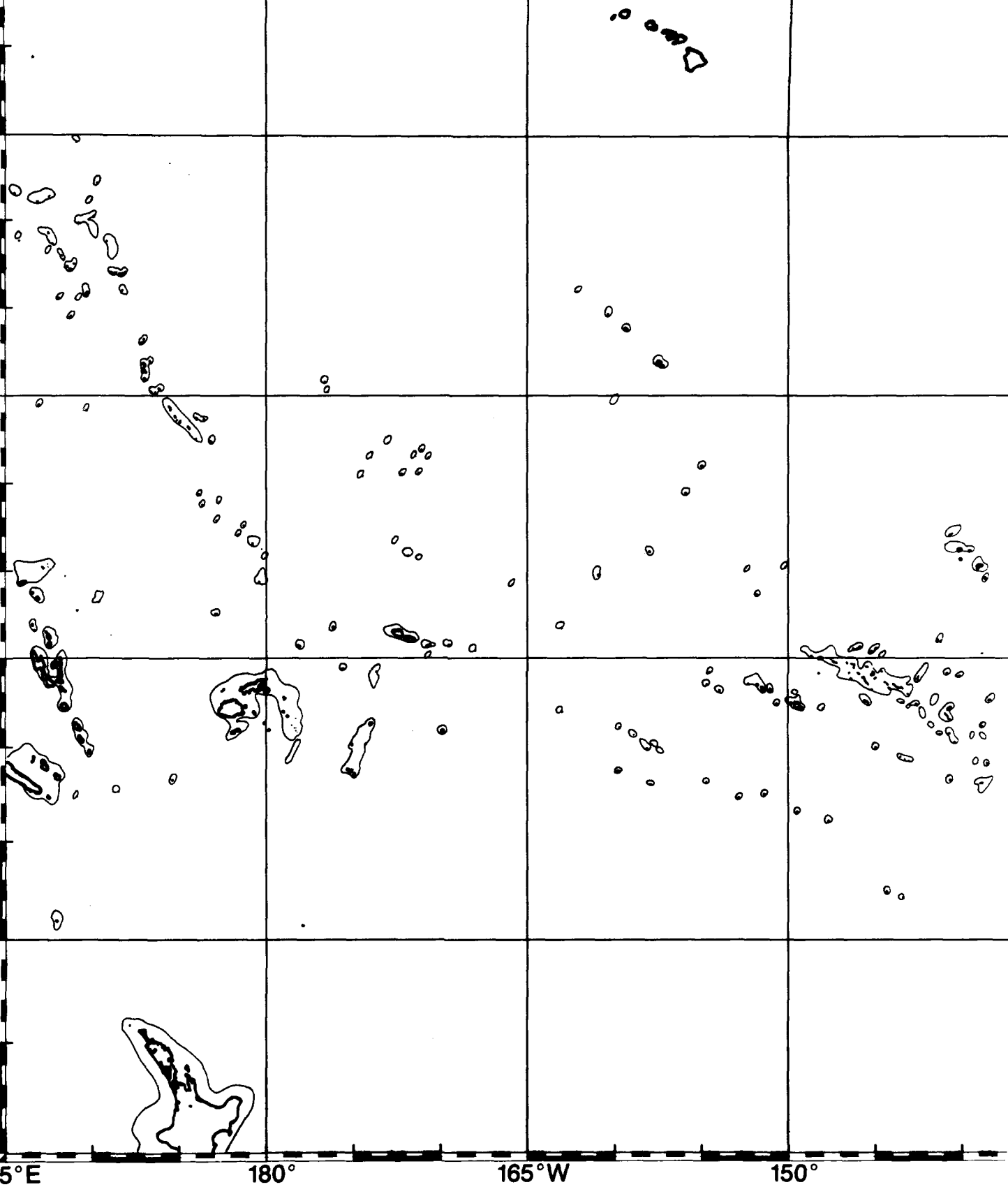
165°E

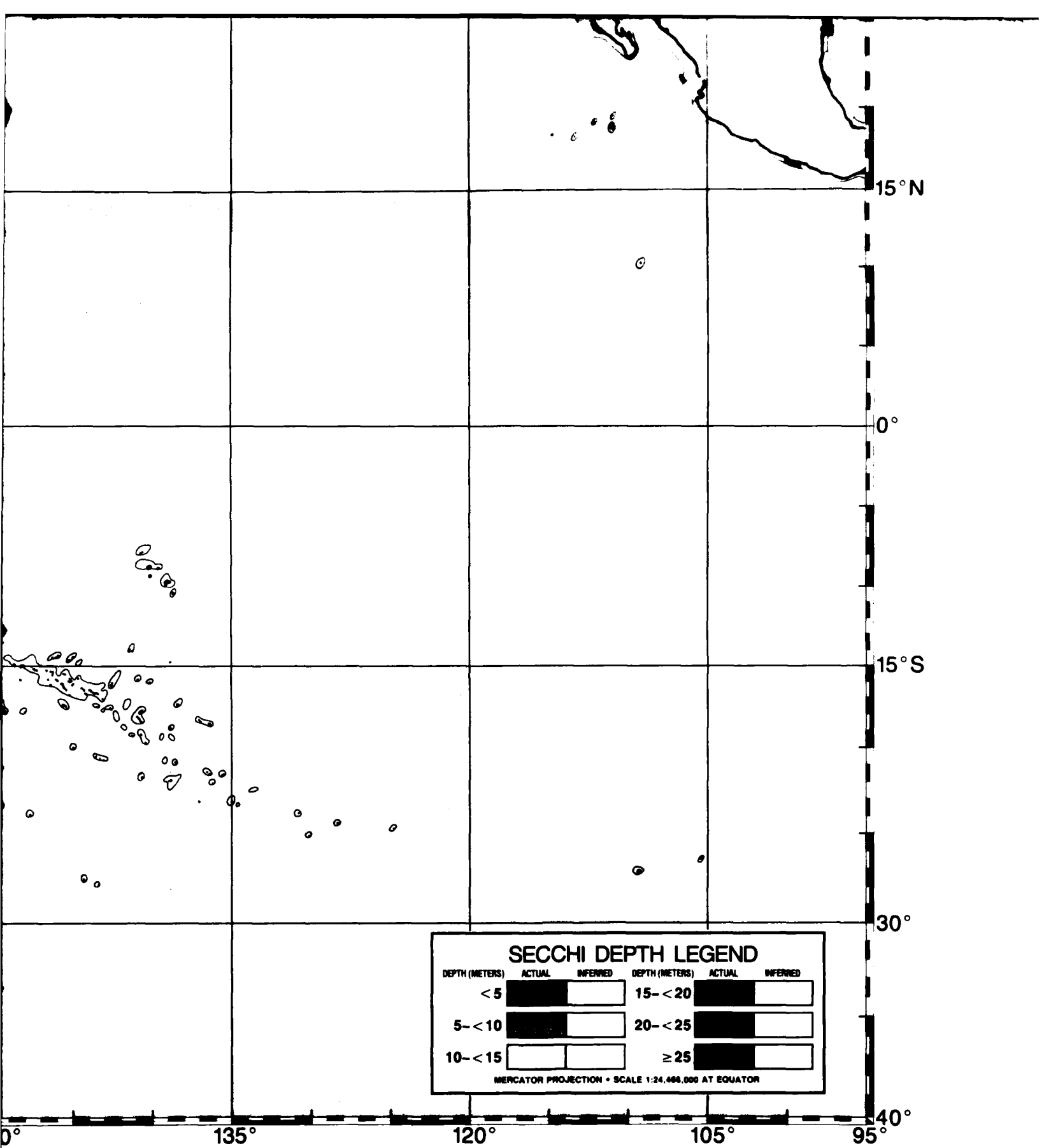
180°

165°W

150°

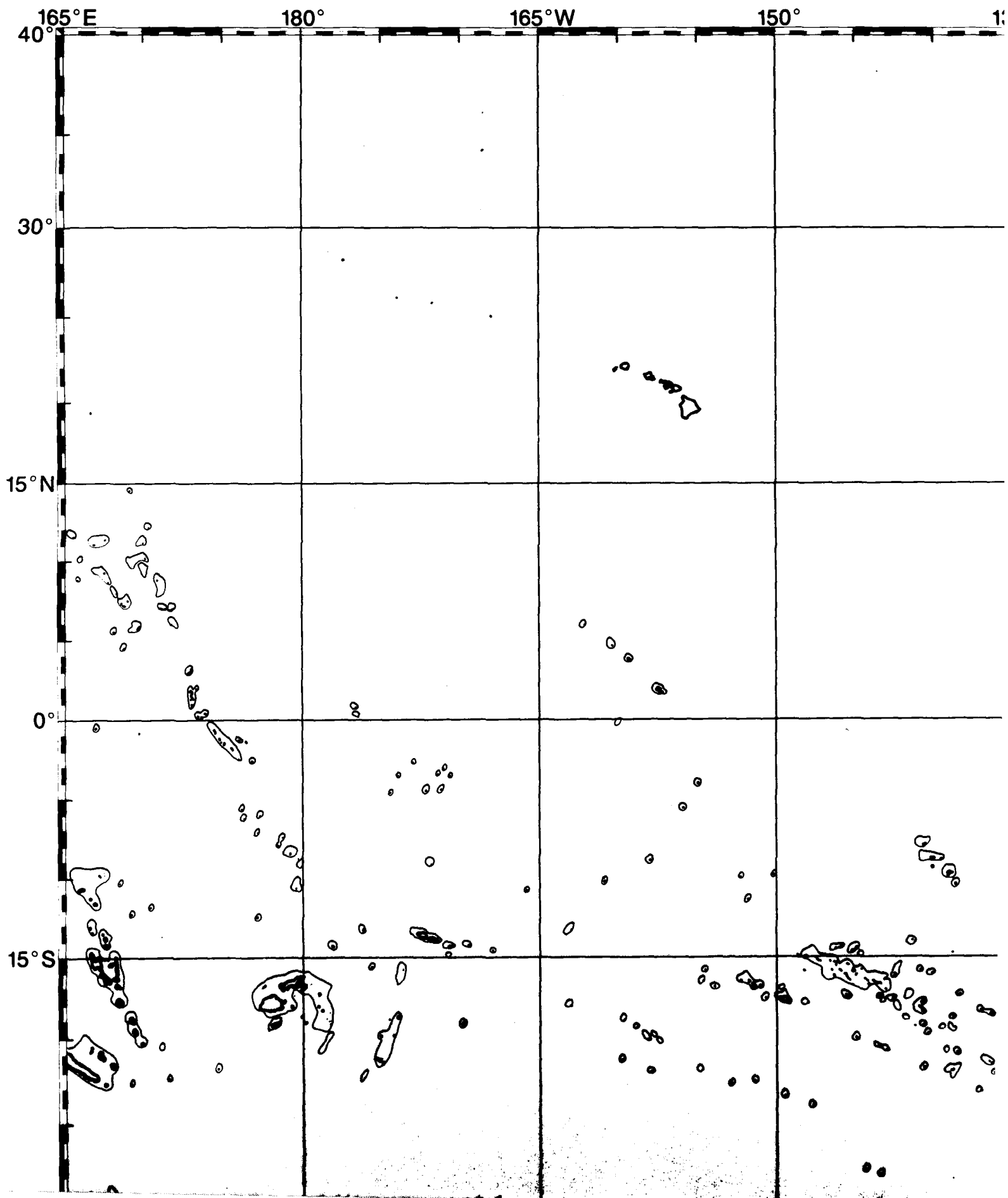
PLATE XVI JANUARY—MARCH

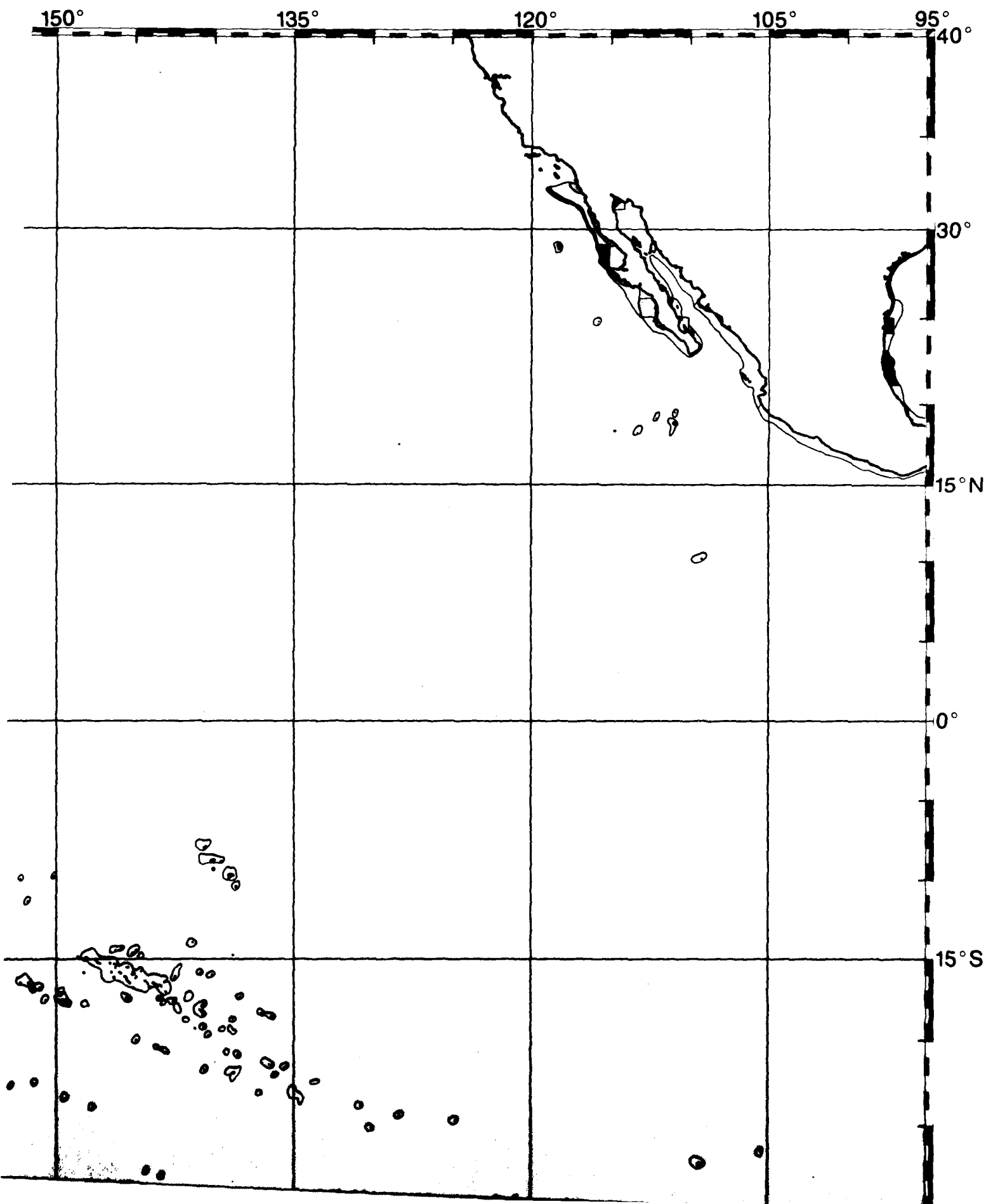




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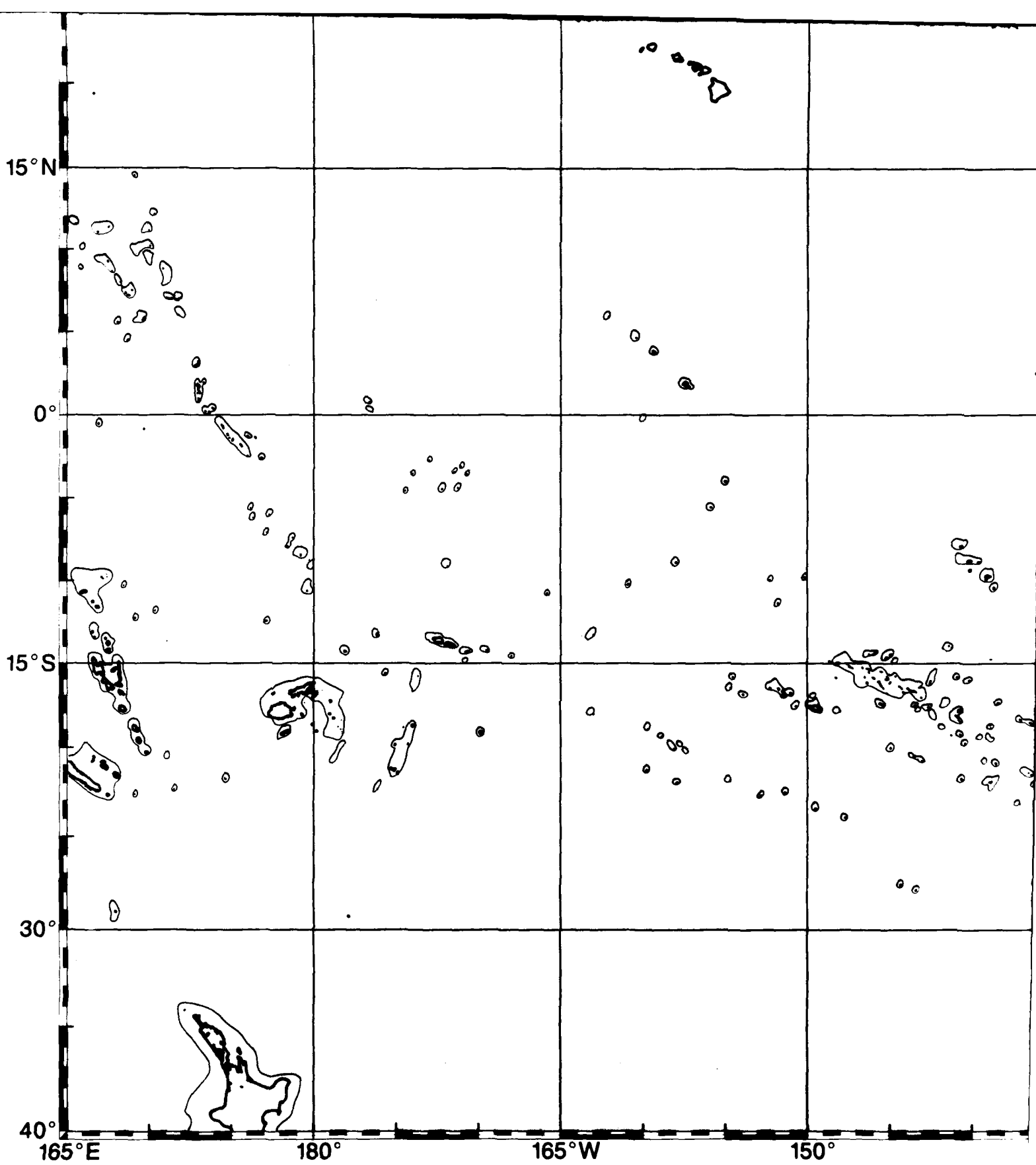
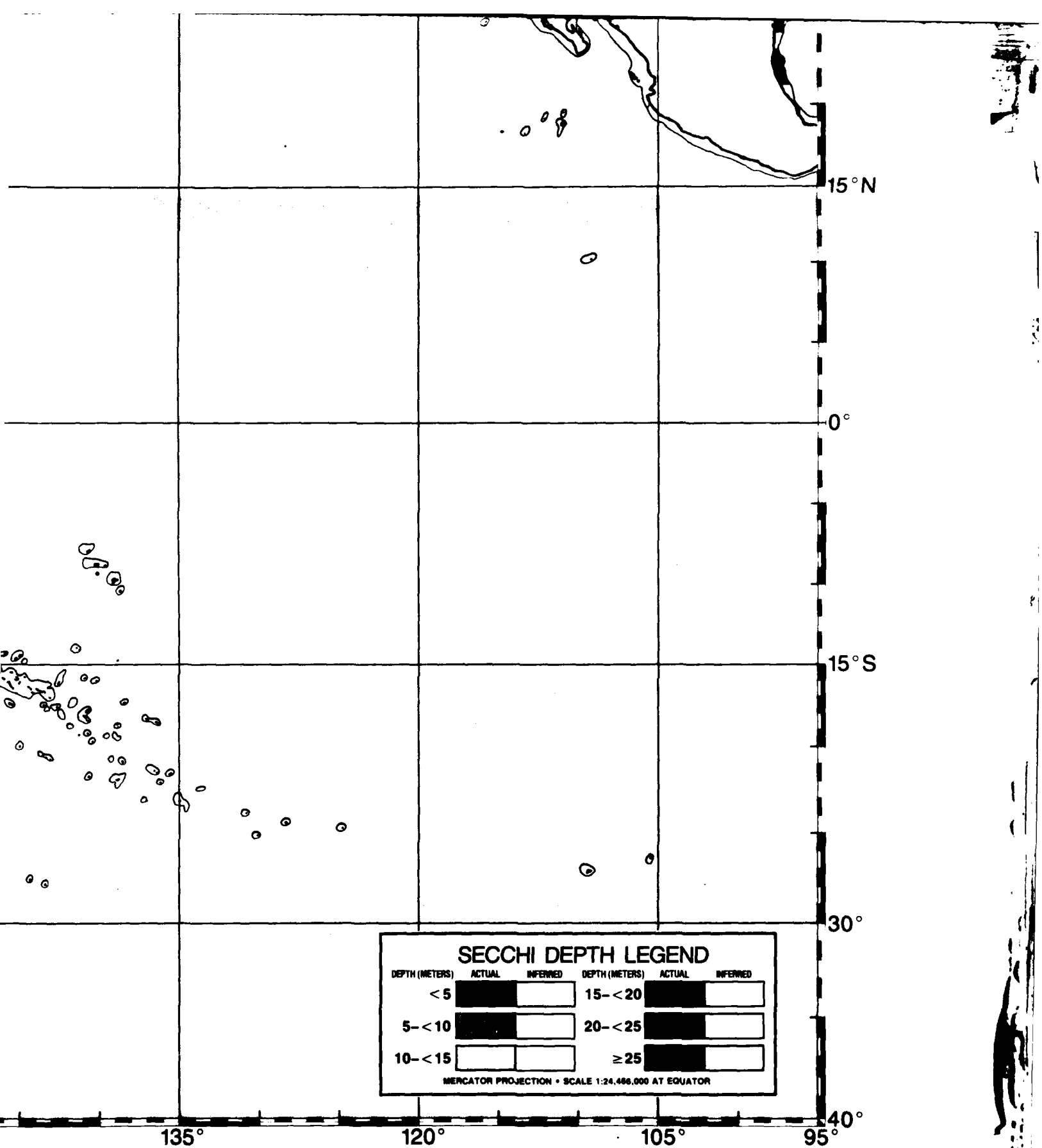
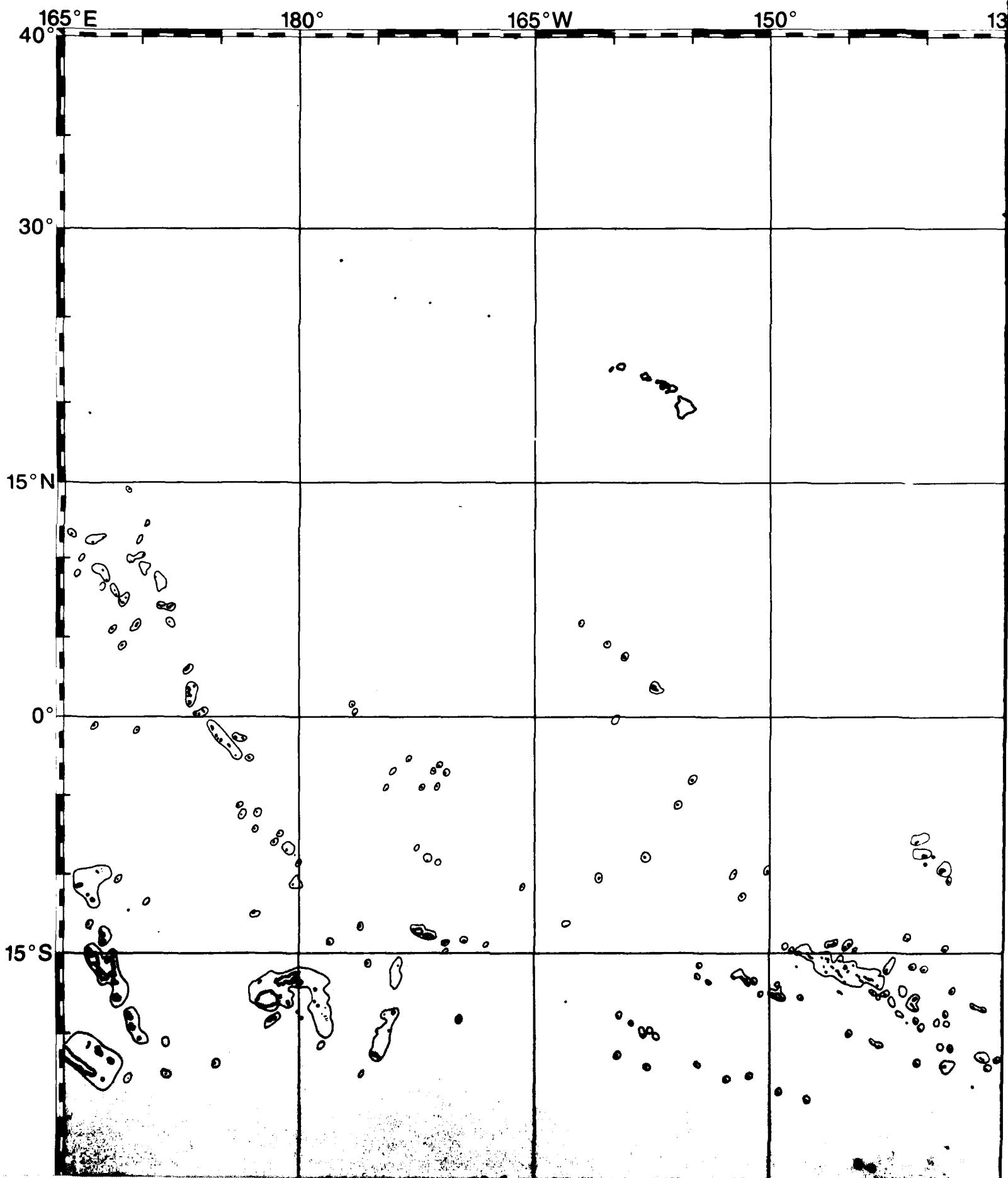


PLATE XVII APRIL—JUNE

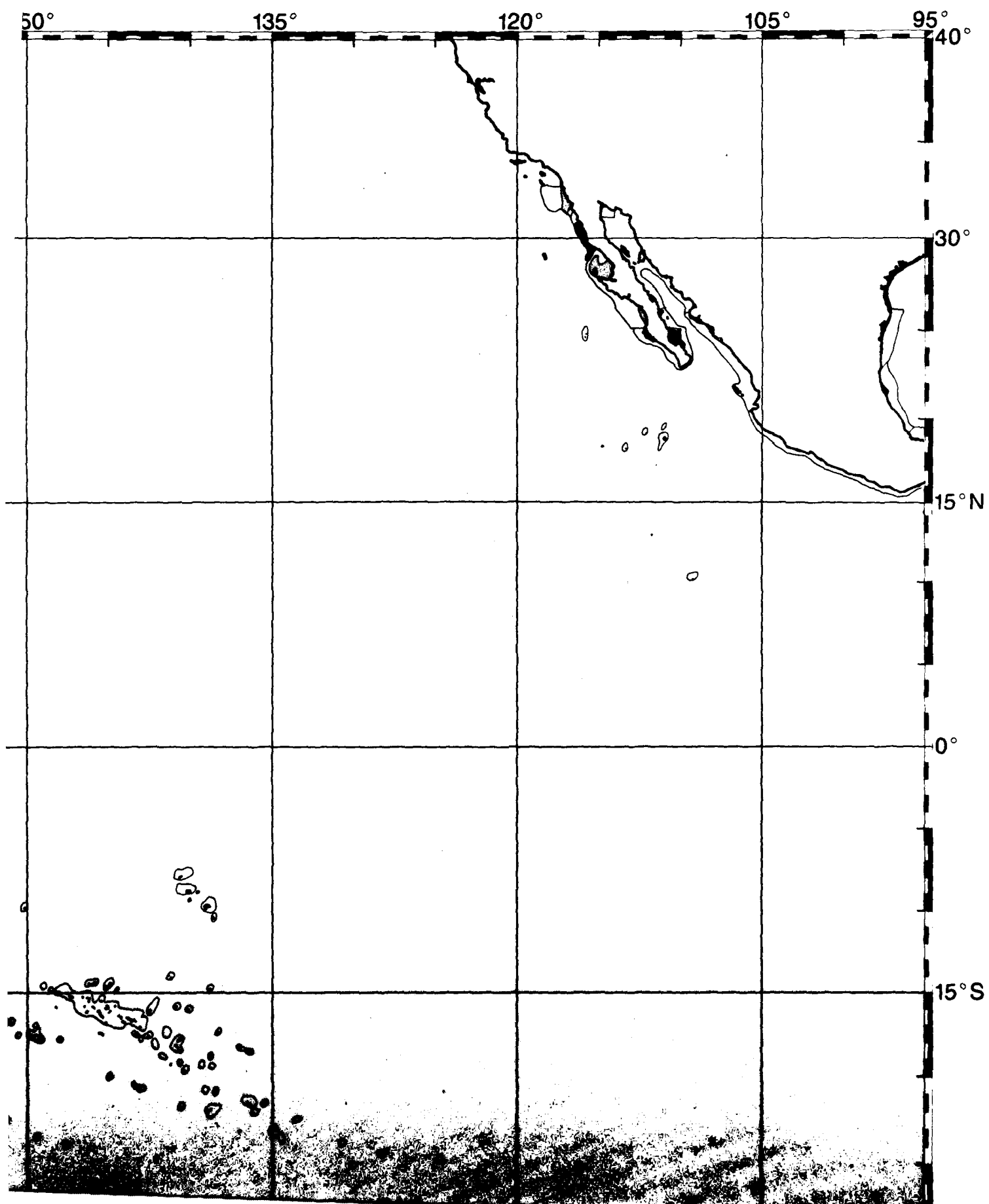


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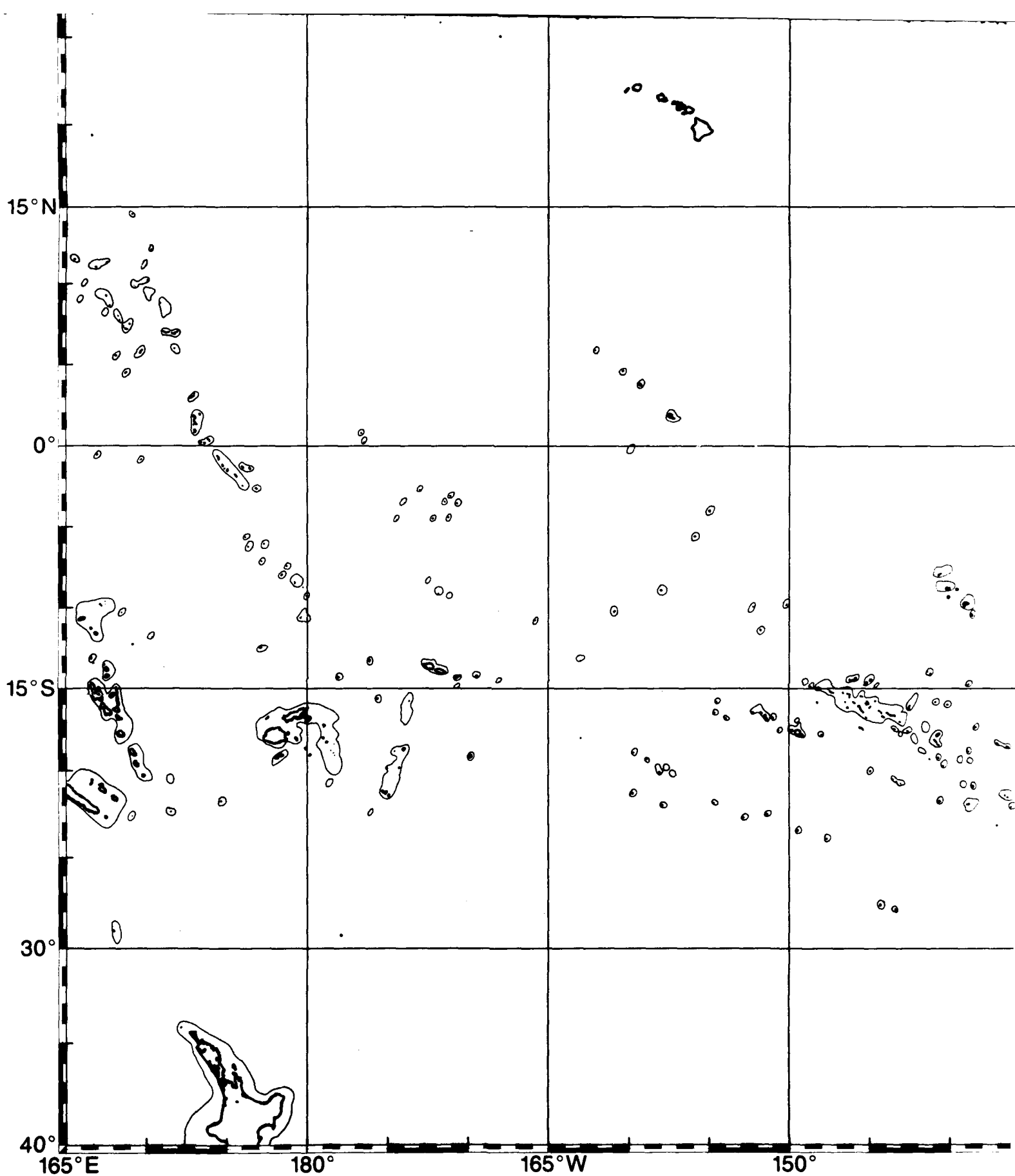
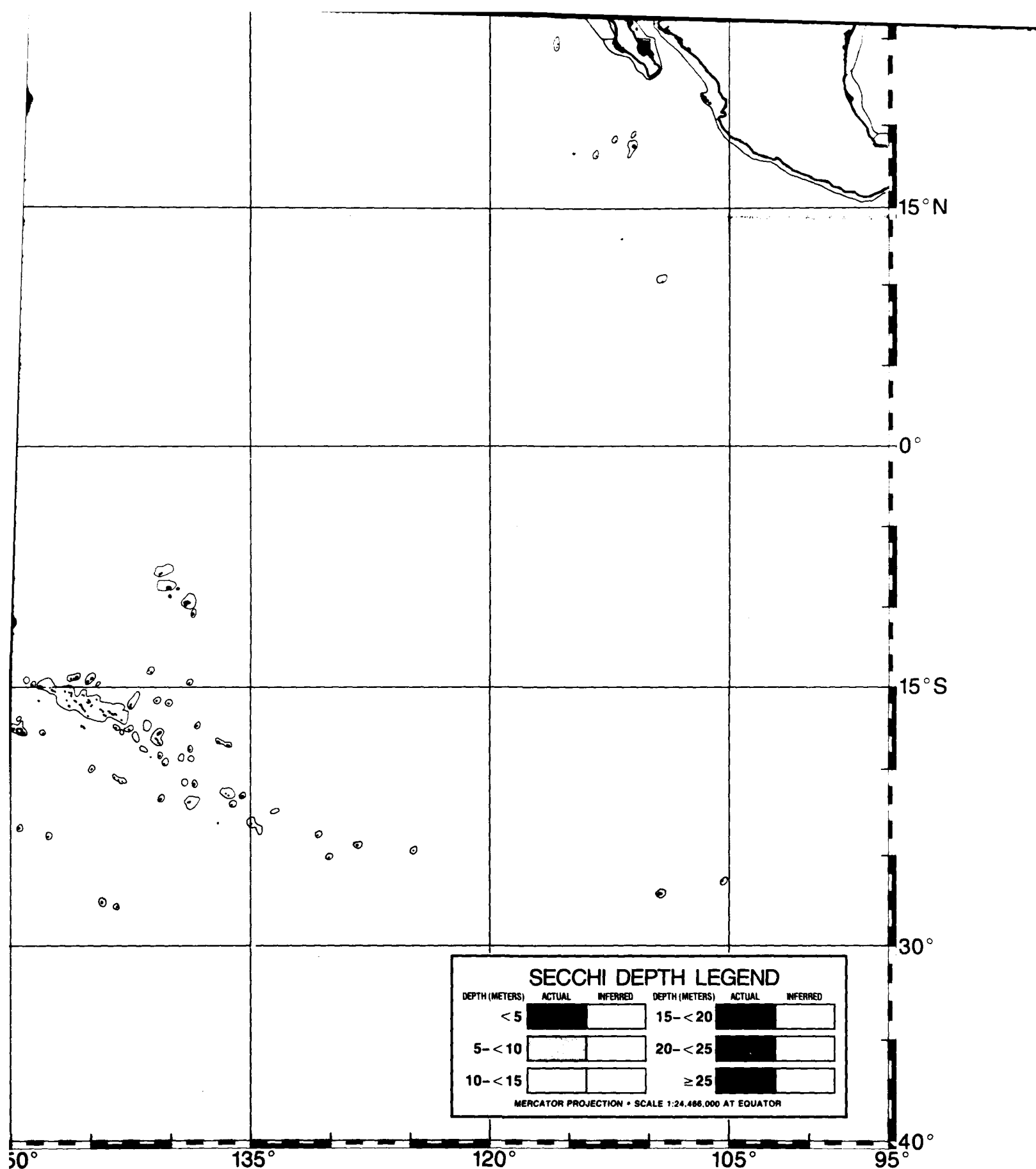
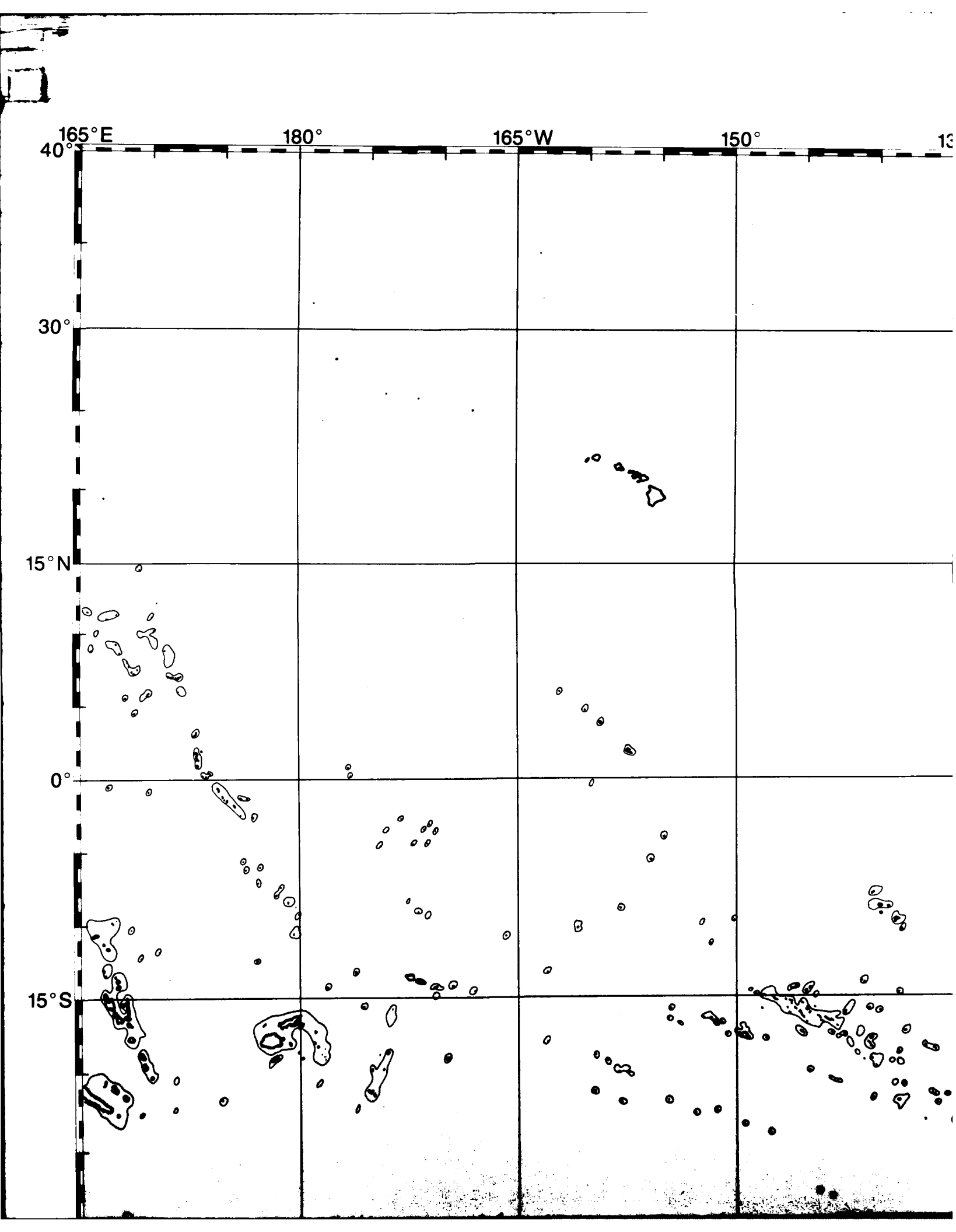


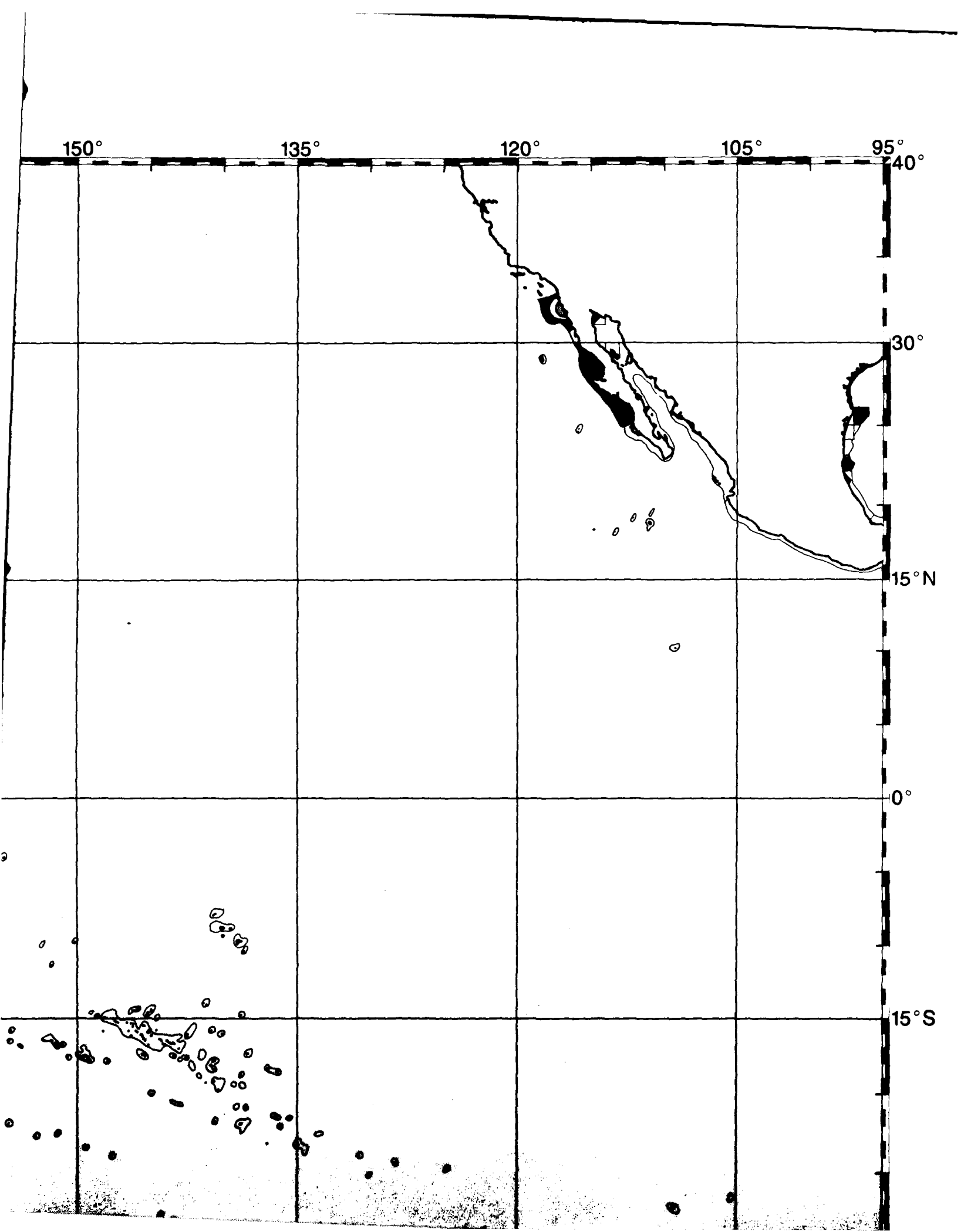
PLATE XVIII JULY—SEPTEMBER



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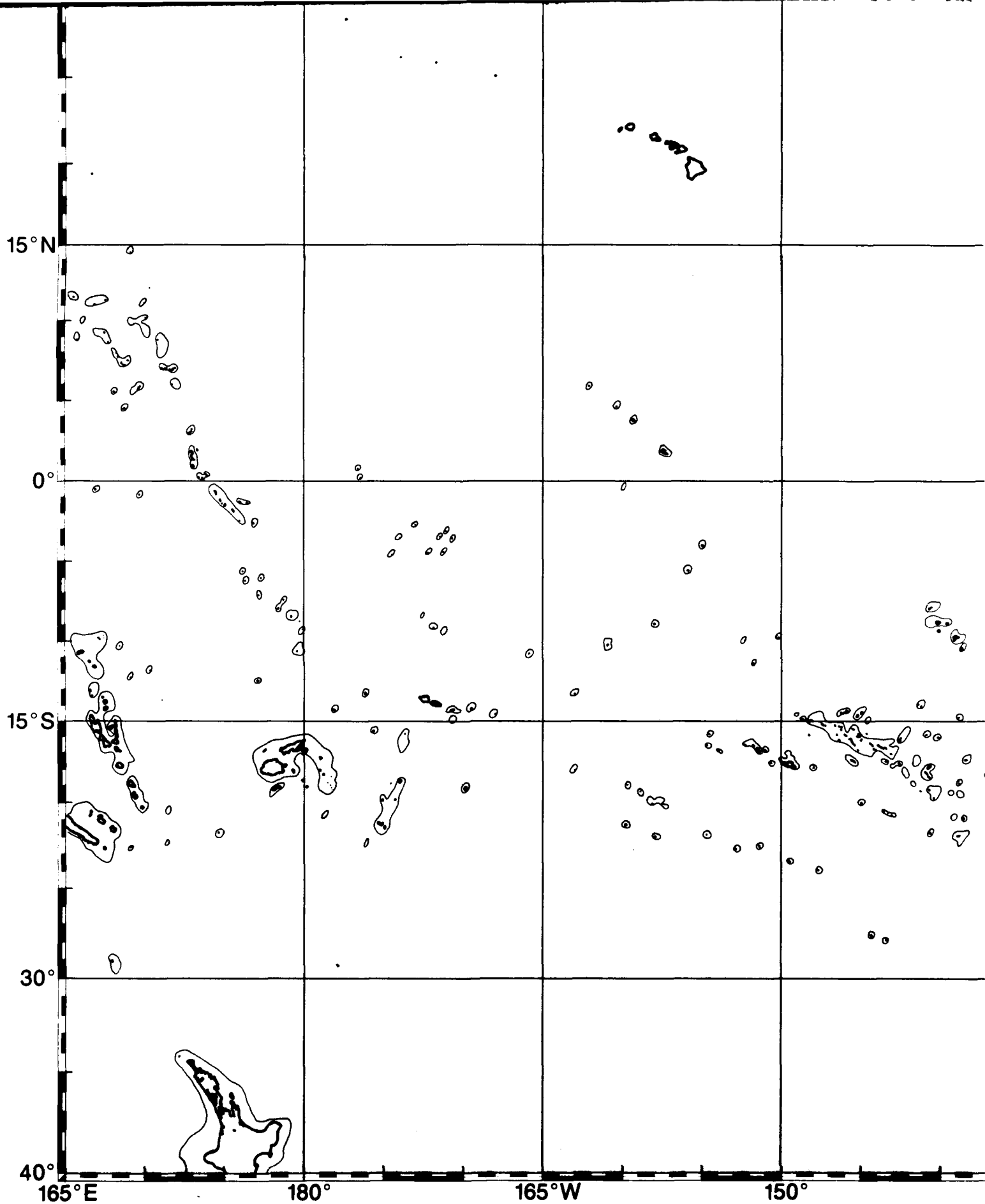
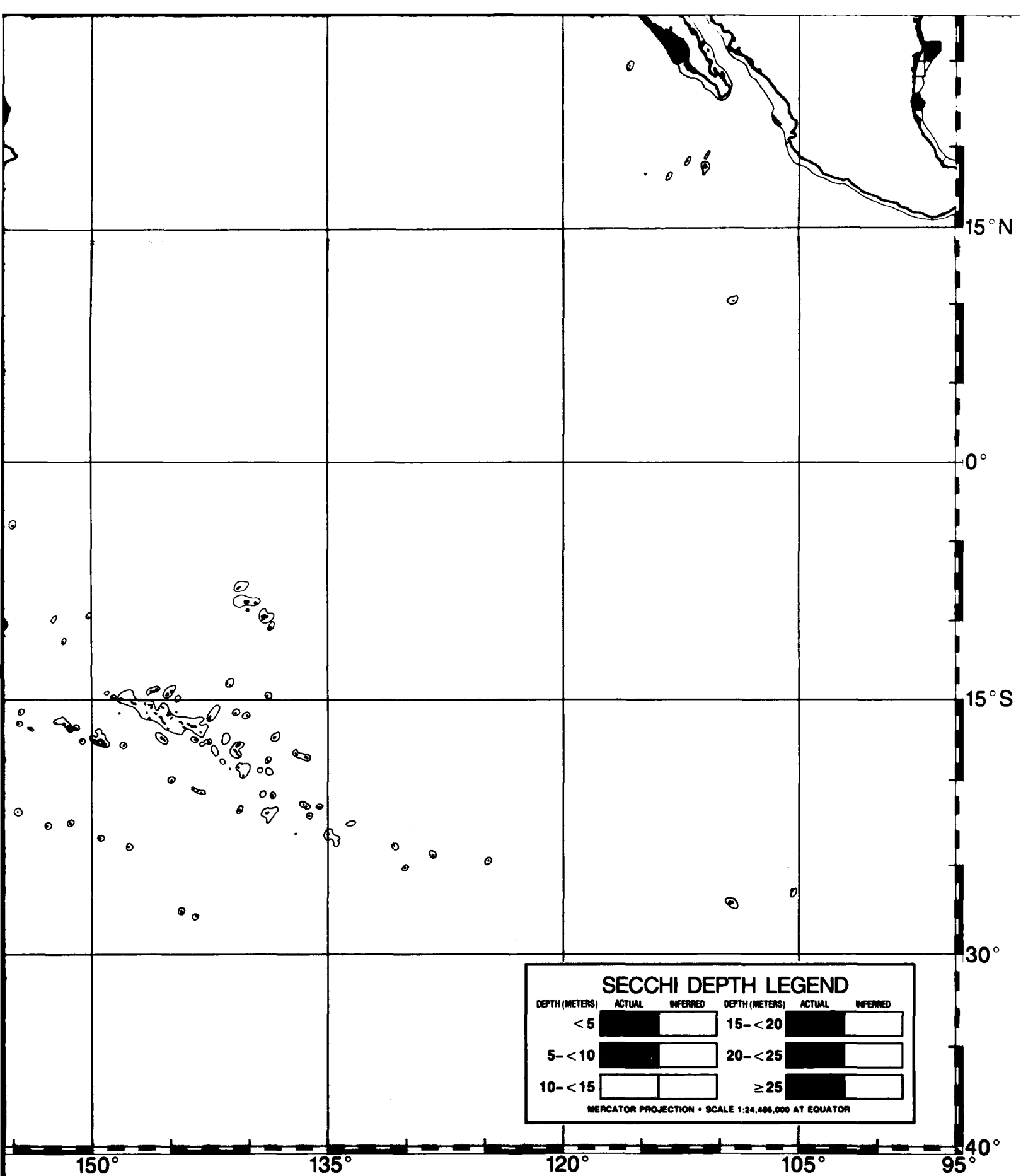
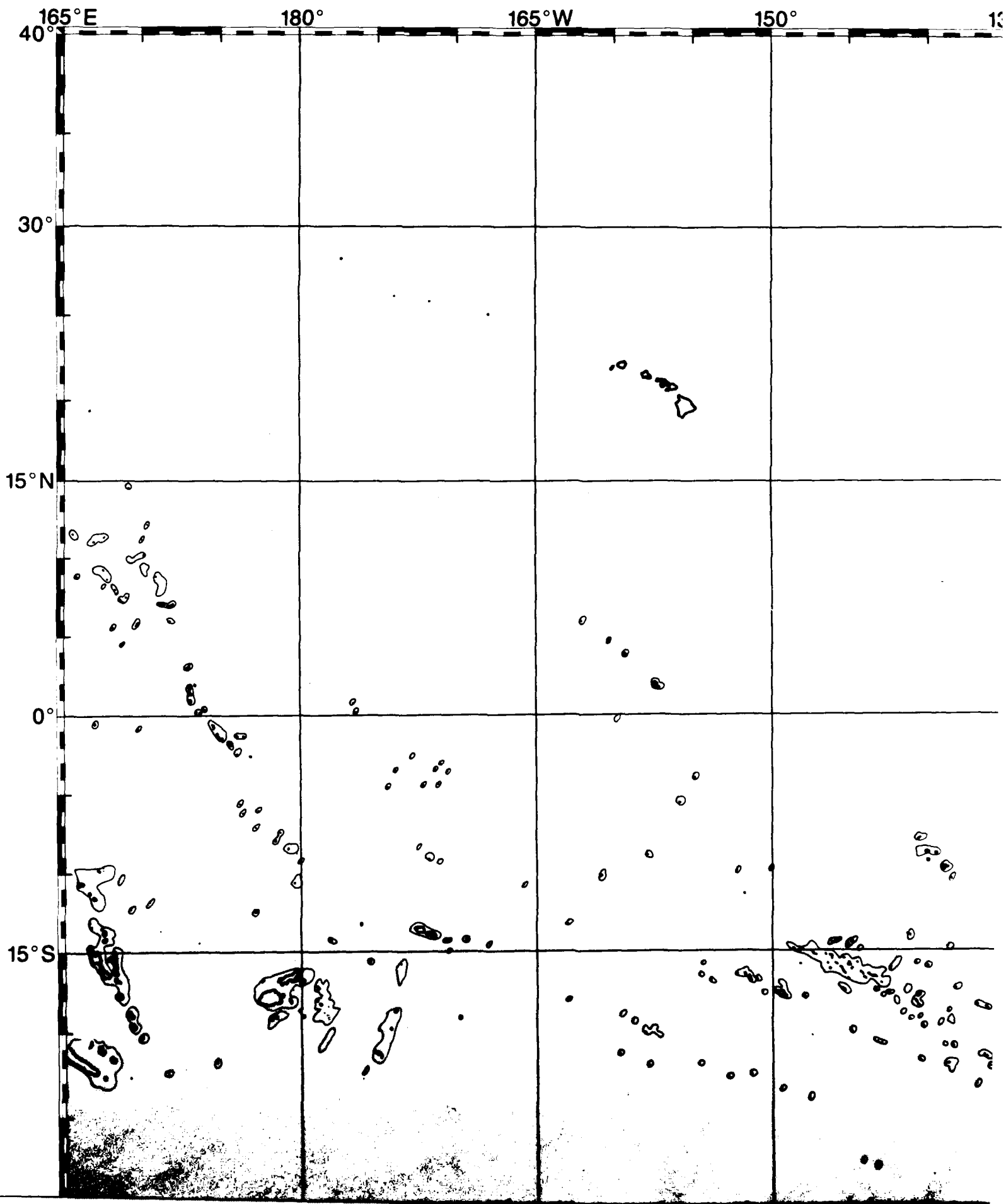


PLATE XIX OCTOBER—DECEMBER

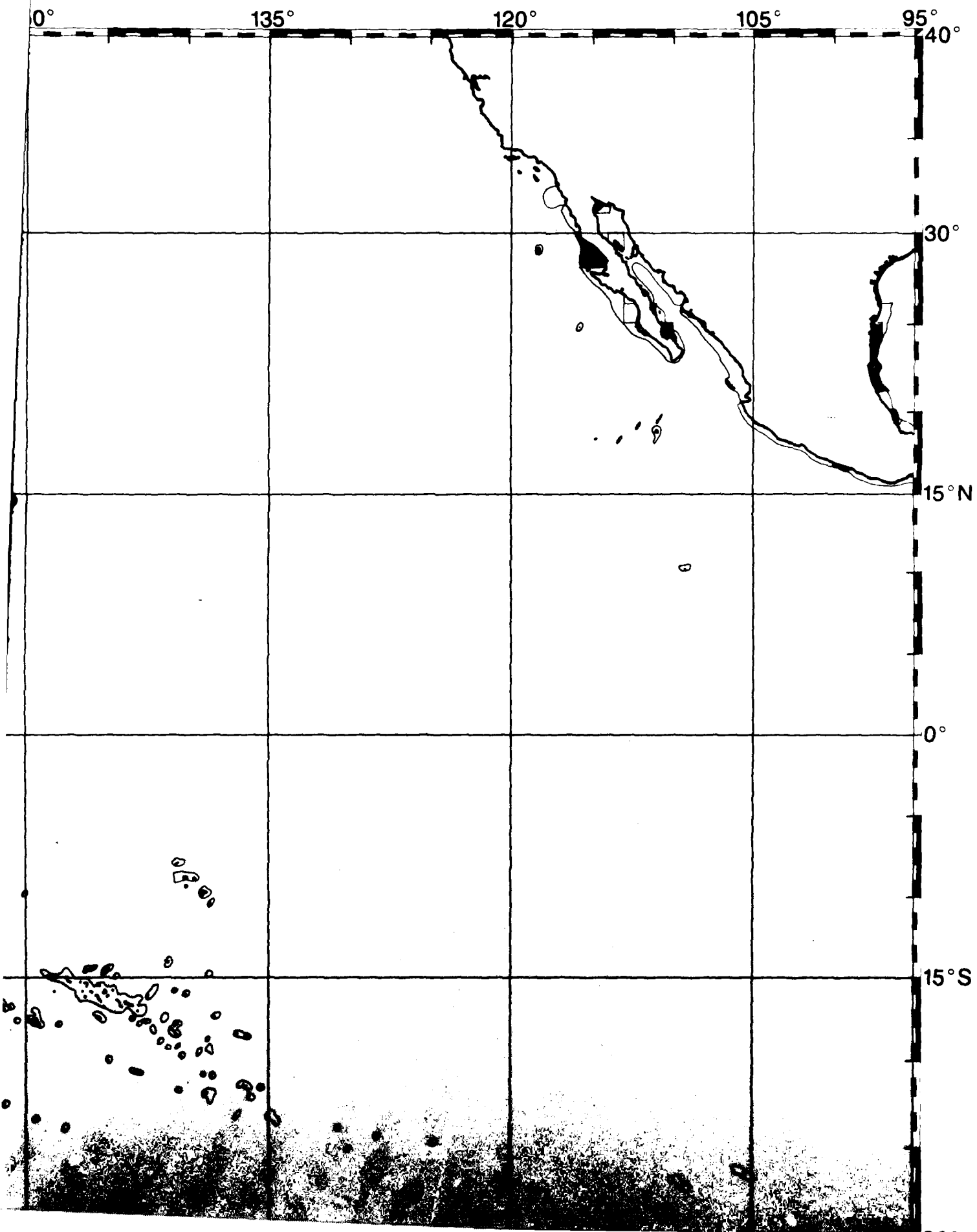


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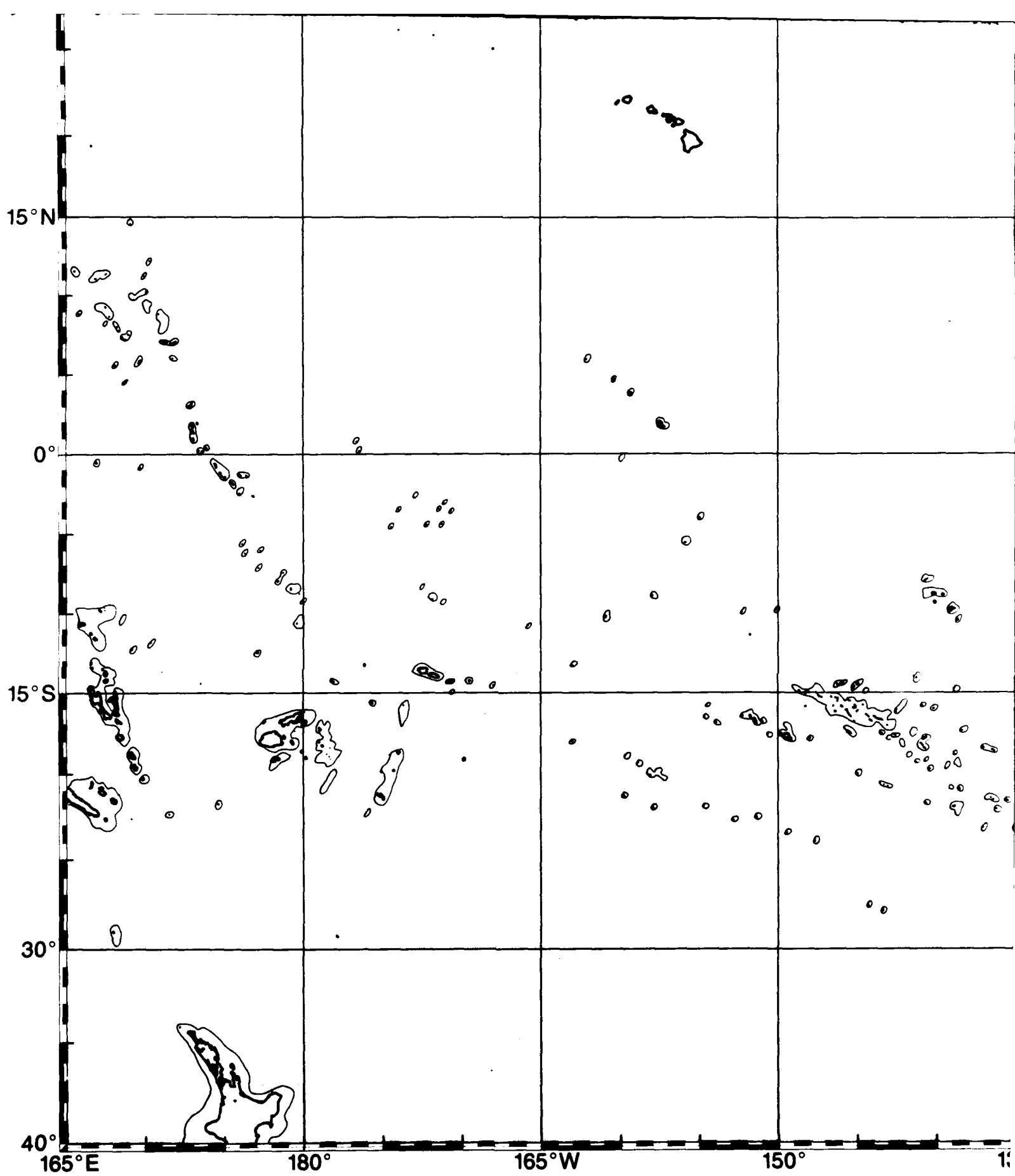
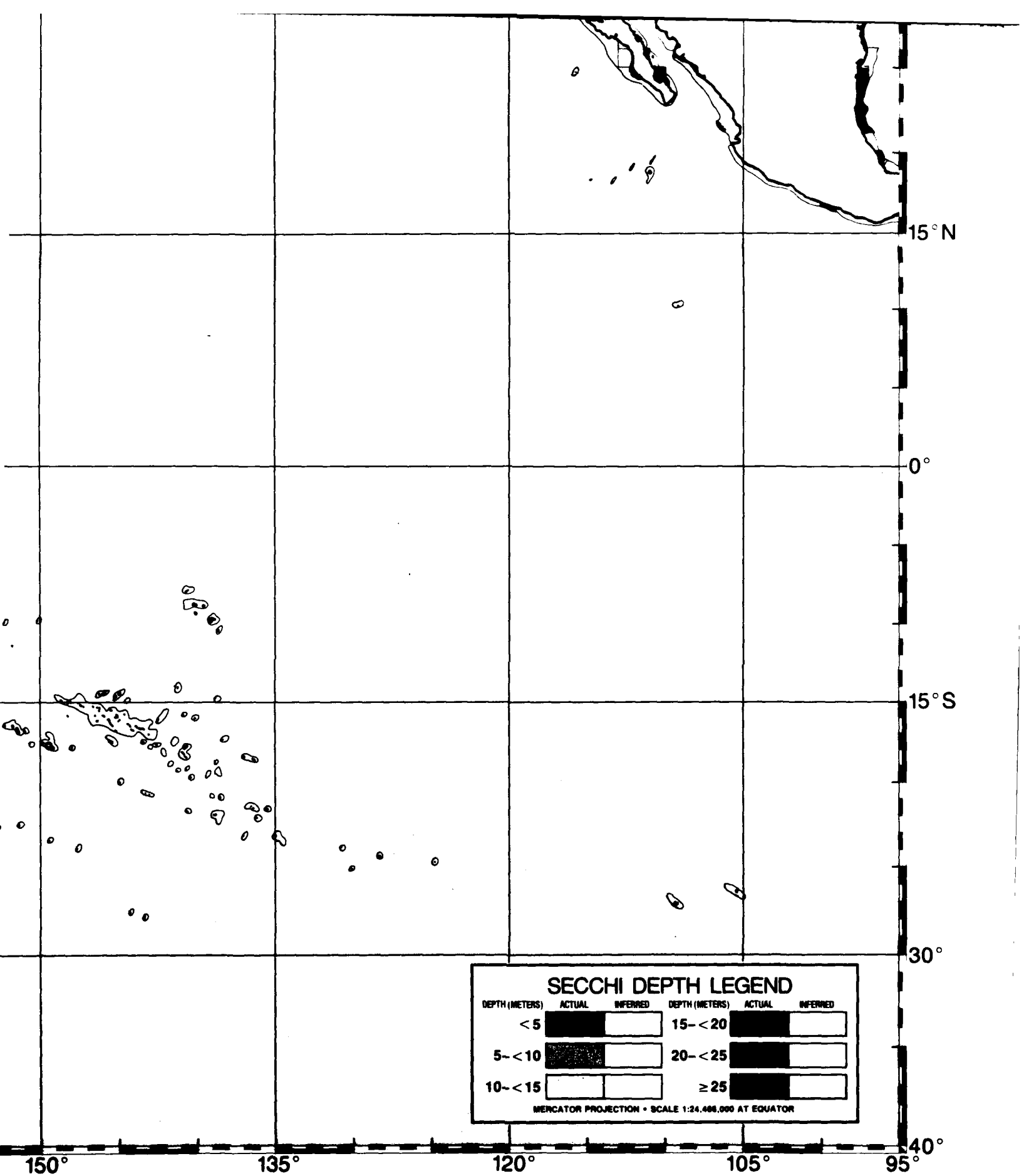


PLATE XX ANNUAL MEAN



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